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ENGINE/AIRFRAME/DRIVE TRAIN DYNAMIC INTERFACE DOCUMENTATION

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APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

This report provides the details of a program that is part of a larger effort designed to provide a complete report of past and present engine/airframe/drive train dynamic interface problems. The problems of vibration related interface compatibility in engine/drive system installations are usually complicated by the inherent coupling of the three major multi-degree-of-freedom systems, i.e., engine, airframe and drive train. The result of this effort is a report documenting dynamic interface problems associated with the Model 369D, Model 500D, and the YAH-64 (AAH). The ultimate benefit will be the accumulation of data which will eventually lead to a solution of generic problems of this type. This report is one of five reports resulting from engine/airframe/drive train dynamic interface documentation efforts funded by the Applied Technology Laboratory. The related reports and their final report numbers are: Boeing Vertol, USARTL-TR-78-11; Hughes Helicopters, USARTL-TR-78-12; Kaman Aerospace, USARTL-TR-78-14; Sikorsky Aircraft, USARTL-TR-78-13; and Bell Helicopter, USARTL-TR-78-15.

Mr. Allen C. Royal of the Propulsion Technical Area, Technology Applications Division, served as Project Engineer for this effort.

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This report pertains to engine/airframe/drive train dynamic interface problems experienced by ~~Hughes~~ Helicopters and the methodology used ~~by Hughes~~ to avoid dynamic interface problems.

The problem of low torsional frequency of the engine/airframe/drive train dynamic system that results from the design philosophy of using a stationary main rotor mast enclosing a separate "floating" torque drive shaft is

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addressed. ~~Hughes'~~ The use of supercritical shafts and vibration isolators are described and mobility methods to preclude engine/airframe vibration problems are discussed.

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PREFACE

This report was prepared by Hughes Helicopters, Division of Summa Corporation, under Contract No. DAAJ02-77-C-0035, funded by Applied Technology Laboratory, U. S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia. The objectives of the program were to provide a report of past Hughes Helicopters engine/airframe/drive train dynamic interface problems and the methods leading to the solution of these problems. Also included is the methodology used by Hughes Helicopters to avoid dynamic interface problems. The documentation presented herein was obtained at Hughes Helicopters, Culver City, from July 1977 to January 1978. The ATL technical monitor for this contract was Mr. Allen C. Royal. The Hughes Helicopters project manager was James F. Needham, who coauthored the final report with Debashis Banerjee, dynamics analyst.

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INTRODUCTION

This report explores the vibration environment of the helicopter with special emphasis on dynamics of airframe, engine, and drive train systems. Concepts have been investigated at Hughes Helicopters to identify means of improving helicopter airframe/engine vibratory compatibility. This has resulted in development of certain unique features that have been incorporated in the OH-6A and YAH-64 helicopters with very good results. The helicopter industry has, in the past, experienced extensive dynamic problems due to excessive engine or drive train vibration. Specific areas have to be investigated properly in order to alleviate these problems. These are discussed in the following report both in reference to Hughes Helicopters and to the industry as a whole.

Hughes Helicopters, because of unique design characteristics that include stationary mast, strap rotor-to-hub retention, friction-damped shaft supports, tuned main rotor pylon structural support design, and supercritical speed drive shafts, has been successful in avoiding the dynamic instabilities and vibrational problems encountered by other helicopter manufacturers. Some of these features will be briefly described in the discussion of the design considerations used to avoid dynamic problems. Following an account of the engine/airframe/drive train interface problems encountered and the corresponding solution, a detailed description of techniques used by Hughes Helicopters to provide engine/airframe/drive train compatibility is given. Some of the areas that will be discussed in this study are:

- Torsional stability of the engine/drive train coupling
- Computerized balancing for supercritical shafting of the tail rotor drive shaft.
- Reduction of rotor N/revolution vibrational loads
- OH-6A engine/airframe vibratory interface

Although engine/airframe compatibility has often been a source of engine vibrational problems, very few published reports exist (see Reference 1). As a result, no general procedure is available in the literature for acceptable standardized engine/airframe compatibility. Reference 2 presents a comprehensive study of the incompatibility and lack of standards in the engine/airframe interface study.

The torsional stability of the main rotor drive system is an important compatibility parameter. Accurate analytical models and proper interface between the engine, fuel control system, and the drive train is of utmost importance as has been outlined in this study.

In an attempt at conserving weight and reducing vibration in the design of helicopters, supercritical speeds for power transmitting shafts are being considered more frequently. Such high-speed shafts require accurate balancing which has traditionally been very expensive and time consuming. Hughes Helicopters has developed a simplified technique for balancing supercritical speed drive shafts. This technique will greatly reduce high-frequency shaft vibrational loads and shaft bearing damage.

As is well known, rotor-induced vibration has been the major source of helicopter vibration problems. With the stringent vibration limits set for present-day helicopters, several approaches featuring rotor isolation have been successful and trends seem to indicate that rotor isolation is the solution to the major vibration problems. Hughes Helicopters has been involved in both active and passive isolation concepts.

Extensive experience has been gained with the use of vertical pendulum (passive) absorbers on the OH-6A helicopter and its commercial

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1. Fredrickson, C., ENGINE/AIRFRAME INTERFACE DYNAMICS EXPERIENCE, AHS/NASA Specialists' Meeting on Rotorcraft Dynamics, Ames Research Center, Moffett Field, California, 13-15 February 1974.

2. Balke, R.W., A REVIEW OF TURBINE ENGINE VIBRATION CRITERIA FOR VTOL AIRCRAFT, Joint Symposium on Environmental Effects on VTOL Designs, Preprint No. SW-70-18, American Helicopter Society, Washington, D.C., November 1970.

counterpart, the Model 500 helicopter (Reference 3). Vibration levels in the crew compartment were reduced over 50 percent for a wide range of flight conditions. Research is also being conducted in the higher harmonic pitch control of the helicopter rotor blades to reduce the N/rev rotor vibrational loads.

Extensive analytical study was conducted for a Model OH-6A to determine compatibility between the engine and the airframe. The accuracies of these studies were corroborated by ground and flight test results. Ground mobility tests, together with analytically determined hub forces, were used to determine T-63 engine vibration loads. A finite-element model for the OH-6A was verified against experimentally determined mobility results (Reference 4). The combined engine/airframe NASTRAN model (see Reference 5) with the main and tail rotor excitation forces was used for final correlation of predicted and measured engine vibration.

The experience gained from solving the dynamic problems on the Models OH-6A and 500D have been very beneficial in avoiding similar problems in the design of the YAH-64 helicopter. Because of more stringent specifications for the YAH-64, better dynamic interface was required between the different systems of the helicopter. Efforts at meeting these requirements are also described in the course of this documentation.

3. Amer, K. B. and Neff, J. R., VERTICAL-PLANE PENDULUM ABSORBERS FOR MINIMIZING HELICOPTER VIBRATORY LOADS, AHS/NASA Specialists' Meeting on Rotorcraft Dynamics, Ames Research Center, Moffett Field, California, 13-15 February 1974.

4. Sullivan, R. J., et al., OH-6A PROPULSION SYSTEM VIBRATION INVESTIGATION, Hughes Helicopters; USAAMRDL Technical Report 74-85, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1975, AD A007225.

5. Vance, J. M., DYNAMIC COMPATIBILITY OF ROTARY-WING AIRCRAFT PROPULSION COMPONENTS, USAAMRDL Technical Report 73-10, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1973, AD 761100.

DYNAMIC INTERFACE PROBLEMS AND SOLUTIONS

Some past dynamic interface problems that have been recognized are: breaking of engine hardware such as external brackets, fuel lines, and engine mounts; drive shaft and coupling failures; and use of exotic (vibration isolation) engine mounts. The military Model OH-6A and the commercial Model 500 helicopter combined have accumulated several million flight hours without any failures that could be related to a dynamic interface problem. The Hughes YAH-64 helicopter has completed Phase I flight testing without incurring any of the above problems or any indication that there will be dynamic interface problems. The following paragraphs discuss the problems encountered in the Hughes Helicopters engine/airframe/drive train dynamic systems.

TORSIONAL STABILITY PROBLEMS OF THE ENGINE DRIVE TRAIN

The unique mounting of the main rotor on the Hughes Helicopters Model OH-6A, or its commercial version Model 500, and on the YAH-64 has an important role in the vibrational environment and stability problems of these helicopters. The use of a stationary main rotor mast enclosing a separate "floating" torque drive shaft results in a low first torsional mode of the engine/rotor/drive train dynamic system. The torsionally soft main rotor driveshaft, combined with a flexible rotor mast, provides rotor isolation and a savings in weight. The torsionally soft drive shaft is an important parameter in determining the torsional stability margin of the engine governing system and may cause persistent torsional oscillations of the power system. The torsional oscillations may be reduced by the use of filters, accumulators, or other modifications in the fuel control system but these changes frequently produce another undesirable characteristic, that of a slow engine power response (rpm droop in transient power change). Methods to avoid these problems are described later in this report.

<u>Model OH-6A</u> — The Hughes Helicopters Model OH-6A, developed in 1964, had a four-bladed main rotor system and was powered with a single Allison 250-C10B (T63-A-5A) engine. Both rpm droop in transient power change and torsional oscillations were observed. However, they were minor and were acceptable to the pilots. The same condition existed with the commercial models, including the Model 500HS. These helicopters also had a four-bladed main rotor system but were powered with an Allison 250-C18A engine.

Model 500D — The Hughes Helicopters Model 500D has a five-bladed main rotor system in place of the previous four-blade configuration and has a change in the tail surface configuration. The prototype Model 500D was flight tested using an Allison 250-C20 engine with a Ceco fuel system installed. The engine power response and torsional oscillations were acceptable.

A production Allison 250-C20B engine with a Bendix fuel control and governor was installed in a Model 500D. Allison utilizes an oil pressure takeoff from a mechanism in their accessory gearbox to measure engine torque in pounds per square inch (psi). Initial flight tests in December 1974 indicated that unacceptable engine torsional oscillations existed. The engine torsional oscillations occurred during high power operations at a frequency of approximately 4 Hz with 4 to 6 psi peak-to-peak (p-p) torque. Additional flights exhibited damped torsional oscillations of ±2.5 psi and steady state torsionals of ±1.5 psi. This condition was unacceptable to both Hughes and Allison pilots. These conditions also exceeded the Hughes Helicopters specification, which states that random torque torsionals shall not be greater than 2.5 psi p-p, residuals no greater than 0.5 psi p-p, and engine power droop no less than 92 percent during sea level power recoveries. The torsional oscillations did not cause a structural problem; however, the oscillations could be heard through fan noise, visualized through torque indicator oscillations, and detected as vibrations in the tail rotor pedals and airframe.

From January through April 1975, numerous unsuccessful attempts were made by Allison and Bendix to tailor the engine speed (N_2) governor and the fuel control system to reduce torsional oscillations without appreciably degrading the engine response. One configuration, using a torsional filter governor, reduced the damped torsional oscillations to ±1.25 psi and a steady state torsional of ±0.5 psi. These values were considered marginally acceptable to the pilots.

In April 1975, Allison requested additional torsional stiffening of the main rotor drive shaft. In reviewing this request with the Hughes Helicopters dynamics personnel, the torsional stiffness of the shaft was increased by increasing the drive shaft wall thickness to provide the same drive system natural frequency (4.1 Hz) that exists with the four-bladed rotor systems. Elastomeric lead-lag dampers had been incorporated in the main rotor hub system, which resulted in an additional 5-percent increase in the main rotor drive system natural frequency.

The final engine/fuel control system configuration consisted of the Allison 250-C20B engine with a Bendix fuel control system on which an Allison kit (P/N 6851488) is installed. The kit consists of an accumulator and is used to dampen torsional oscillations in the fuel control system. The engine/ fuel system configuration, together with the stiffened main rotor drive shaft, reduced the torsional oscillations to acceptable limits without degrading the engine power response. The final configuration was approved by pilots from Allison, the Federal Aviation Administration, and Hughes Helicopters in August 1975.

Model YAH-64 — During Phase I of the YAH-64 flight test program, the torsional stability and engine droop characteristics were generally acceptable by the pilots. Monitoring equipment showed engine rpm droops slightly larger than the specification Hughes Helicopters requested of General Electric. Work is presently in progress with General Electric to improve engine droop characteristics, yet maintain a reasonable gain margin at the critical torsional frequency of the main rotor drive system.

DYNAMIC VIBRATIONAL PROBLEMS OF THE AUXILIARY POWER UNIT (APU) AND FAN SHAFTS

This section discusses two different dynamic problems associated with the APU shaft and the fan shaft, respectively.

APU Shaft — A schematic view of the APU shaft is seen in Figure 1. The APU shaft reached its resonance peak at 114 percent of its nominal speed. At this speed the diaphragm coupling (B) on the shaft failed due to excessive vibrational loads. The first failure occurred in January 1976.

The basic problem was in the determination of the stiffness of the APU shaft. The stiffness of the bearing supports (A) (which are located within the accessory gearbox) could not be accurately defined. This caused the critical speed of the shaft to fall below the value that was predicted. The problem was overcome in two steps.

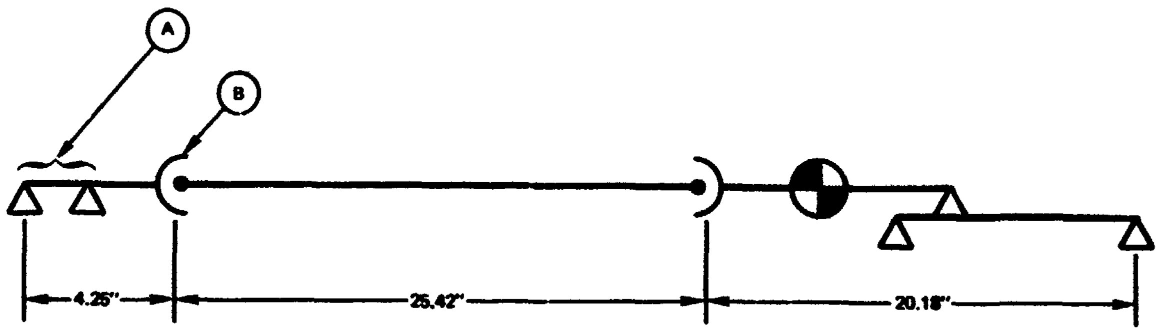

Figure 1. Schematic view of APU shaft.

The bearing (A) was stiffened. This was done by introducing an additional pilot (Pilot 1 - Figure 2) in the spline coupling bearing support (A) and by reducing the tolerance in pilots 1 and 2 to a minimum. The use of a double-piloted spline reduced the free play between the coupling shafts. This effectively stiffened the APU shaft and also minimized the imbalance of the rotating shaft.

The second modification was made by moving the diaphragm coupling (B) closer to the bearings (A) by a distance of 0.66 inch. This reduced the vibrational displacement of the diaphragm coupling.

Fan Shaft – The shaft on which the fan for the infrared (IR) suppressor is mounted had a resonance vibrational problem that was first observed in September 1975. The fan shaft forward end vertical nature frequency of approximately 78 Hz was close to the shaft rotational speed as denoted in the fan plot (Figure 3). The resonant vibration resulted in fatigue failure of the shaft supports. The bearing supports that were made of bent plate sections were replaced by machined supports. The resultant stiffened bearing supports reduced the vibrational loads to acceptable levels.

The shaft rpm was above the critical speed. As will be explained later, power shafts may be run at supercritical speeds without any instability

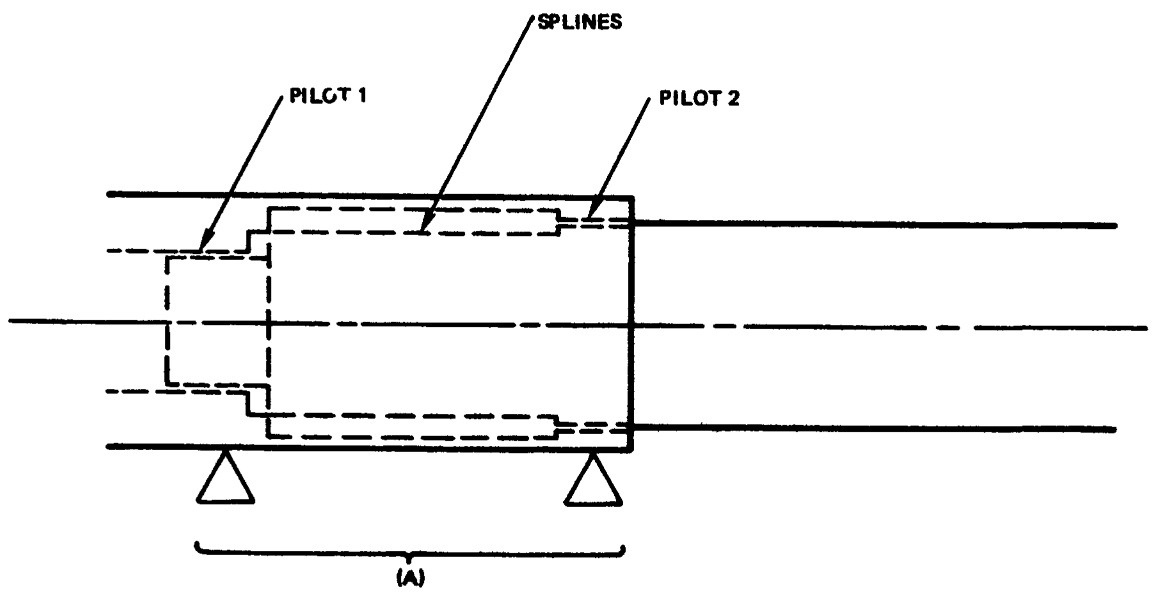

Figure 2. Sketch of double-piloted spline coupling of the APU shaft.

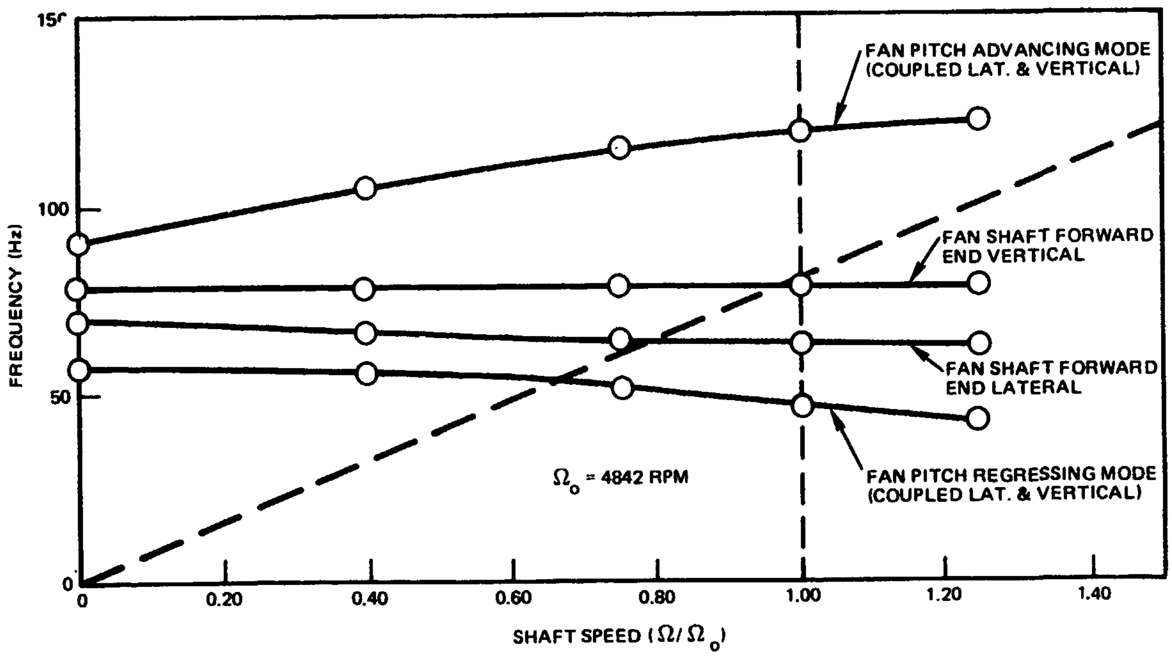

Figure 3. Modal frequency plots for the fan shaft.

problems if rigid mounting and structural flexure coupling elements are used.

The fan was removed from the YAH-64 Phase II configuration when its IR function was replaced by the Hughes Helicopters-developed engine exhaust infrared suppression system. The suppressor consists of the two major components shown schematically in Figure 4. An adapter attaches to the engine flange and directs the exhaust into three rectangular ejector mixer nozzles. These mixer nozzles both cool the engine exhaust gas by introducing cold air and prevent a direct view into the hot internal parts of the system. An adapter attaches and seals the mixer nozzles to the engine cowl, which permits the engine bay to serve as a plenum for the ejector cooling air used for exhaust dilution.

<u>Shaft Problems</u> — The dynamic stability and vibrational problems of the APU and fan shafts are, to a great extent, dependent on the overall vibrational environment of the engine drive train. The problems that have been posed in this regard are:

- How to accommodate translational and rotational displacements between the different drive elements of the transmission system.

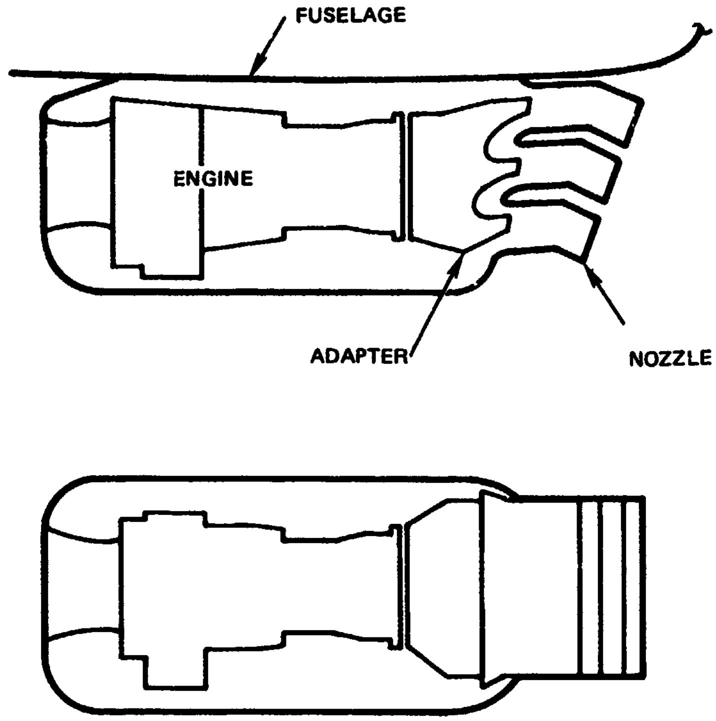

Figure 4. YAH-64/Suppressor components.

- How to provide translationally stiff supports at the ends of the transmission shafts.

The use of articulated rotors isolates the rotor vibrational loads from the drive train. The low vibrational loads transmitted by the articulated rotors used by Hughes Helicopters permits the drive shafts to be rigidly mounted. The relative displacement between components is small and, hence, is accommodated by structural flexure elements (Bendix diaphragm couplings) at the ends of the shafts rather than by spherical splines or other sliding-mechanism-type elements.

The translational stiffness of the supports at the ends of a shaft is difficult to predict and may cause the critical speed of the shaft to fall below the operating speed if the stiffness is less than estimated. In this case, mechanical instability results when using spherical splines or other friction-producing elements (with dampers located in the rotating system) as compared to the use of flexural diaphragm couplings with dampers mounted in the nonrotating system where supercritical speed does not lead to any critical problems. This will be considered in more detail in the study of supercritical speeds of the tail rotor shaft.

EFFORTS IN PREVENTING INTERFACE PROBLEMS

As outlined in the introduction, Hughes Helicopters has avoided potential engine/airframe/drive train interface problems by the use of well-developed analytical tools substantiated by ground and flight tests. Since these techniques helped in reducing the interface problems, some of them will be discussed in detail as preventive measures in the dynamic interface study.

ANALYSIS FOR TORSIONAL STABILITY OF THE ENGINE DRIVE TRAIN

As explained before, torsional stability due to the engine fuel control system has been a problem requiring extensive analysis and a study of the electronic and hydromechanical components of the engine drive system. Some of the main features of this analysis done on the YAH-64 are outlined below.

A block diagram of the engine fuel control loop is shown in Figure 5. The electronic control unit (ECU) monitors the error between the turbine speed and a reference speed. It shapes (or tailors) this error message and sends a signal to the gas generator in terms of percent of gas generator speed. As the name implies, the hydromechanical unit (HMU) consists of the mechanics of the fuel control system and the dynamics of the gas generator.

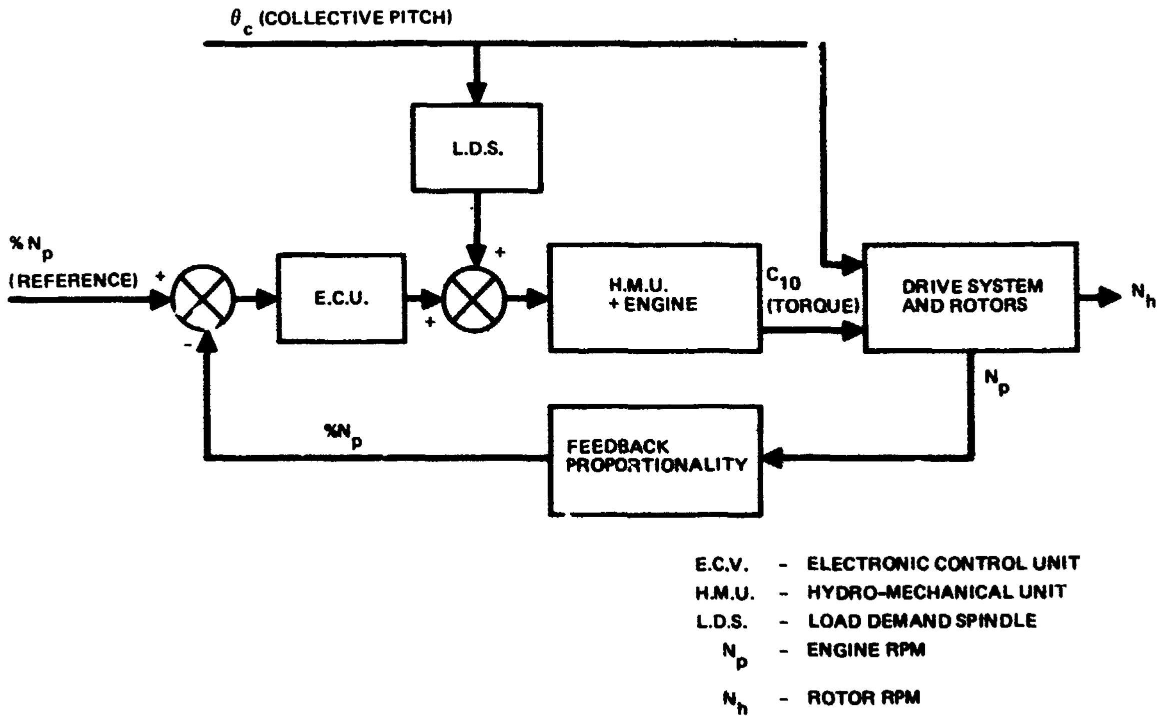

Figure 5. Block diagram of engine fuel control system.

The inputs of the HMU units are the ECU output and load demand spindle (LDS) unit response to stick position change. A lumped spring/mass/damper representation of the rotor system model is shown in Figure 6.

The open-loop stability analysis in terms of Bode plots is studied. The phase and gain stability margins are indicated in Figure 7. The critical factor, however, is the peak in the gain curve, which is the determining point for the torsional stability of the drive train. Generally, a minimum gain margin or 6 dB at the critical frequency is desirable to account for inaccurate modeling due to nonlinearities in the system. Increasing the gain in the ECU would improve the rpm droop characteristics, but would at the same time decrease the gain margin at the critical frequency leading to torsional instability. Hence, the gain should be chosen to compromise between transient response and the stability margin of the engine governing system. Some of the other parameters found to have a significant effect on torsional stability are the characteristics of the main rotor lag damper and the torsional stiffness of the main rotor shaft. Since the lag dampers are present for ground resonance reasons, they cannot be modified significantly without degrading the ground resonance characteristics of the helicopter. The gain margin at the critical frequency (as denoted in the Bode plot) is directly proportional to the torsional stiffness of the main rotor shaft. Hence, the torsional stability margin increases with increasing main rotor shaft torsional stiffness. These analytical models are verified against ground and flight test results.

Tail Rotor Drive Shaft Design — Hughes Helicopters has successfully used supercritical tail rotor shafts for the Model 500 series helicopters and also for the Model YAH-64. As previously pointed out in the study of the APU and fan shaft vibration problem, the use of diaphragm couplings, as compared to spherical splines or other friction-producing elements, has been beneficial to the use of supercritical shafts. If spherical splines or other couplers with damping effect in the rotating system are used, proper precautions must be taken. In this configuration, mechanical instability will occur at supercritical speeds if adequate viscous damping is not provided in the nonrotating system. Design requirements for dampers in this frame of reference are more stringent. With the use of diaphragm couplings, the damper requirements for supercritical shafts are much less restrictive. Model 500 series helicopters use a tail rotor drive shaft that operates between first and second mode critical speeds. The Phase 1 YAH-64 helicopter used a tail rotor drive shaft that operated between the second and third mode critical speeds. Both of these designs have simple friction dampers that do not normally contact the shaft and are operational only during transitions in order to limit amplitudes of motion when the shaft is passing through critical speeds.

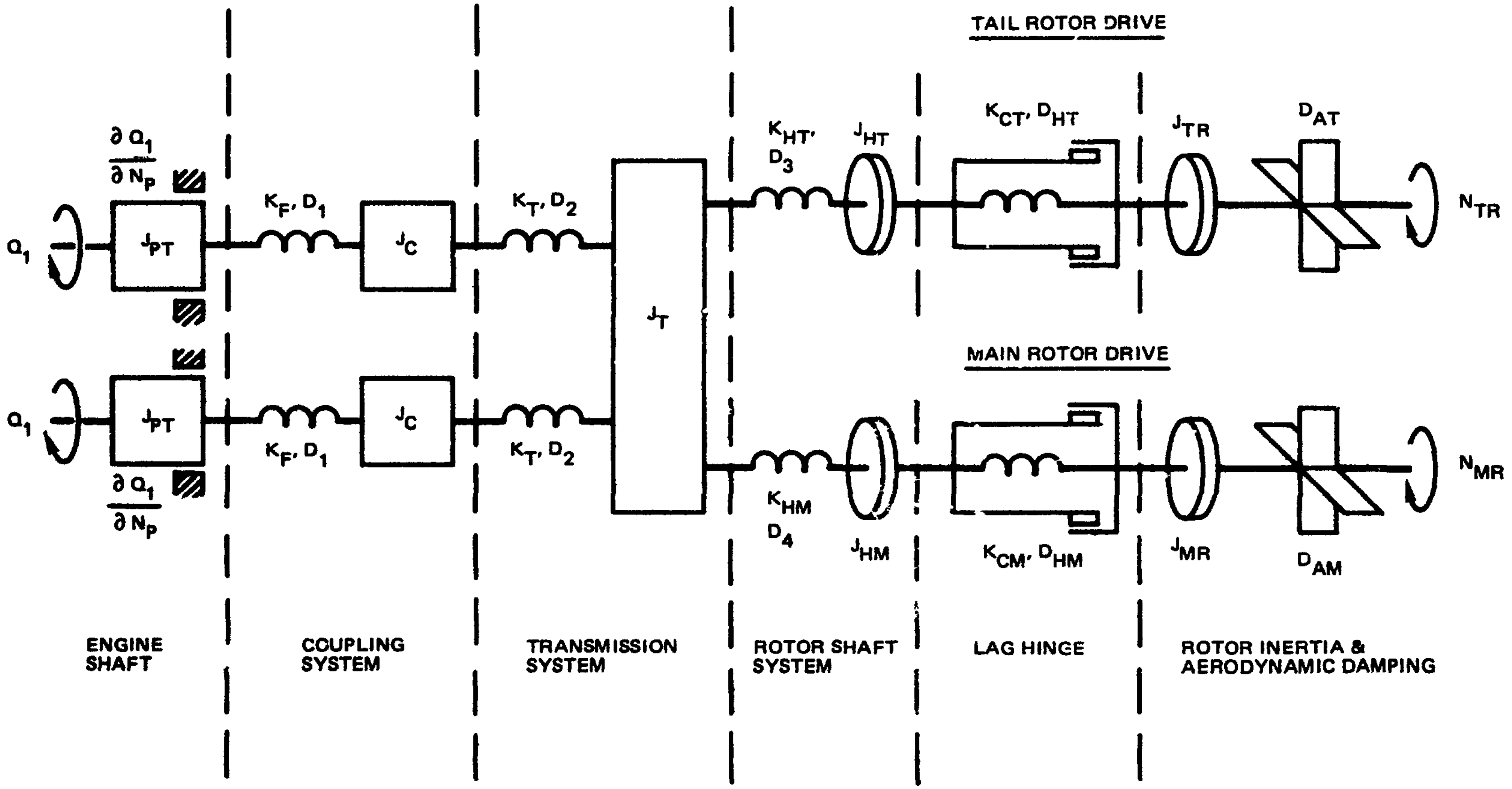

Figure 6. Rotor system block diagram.

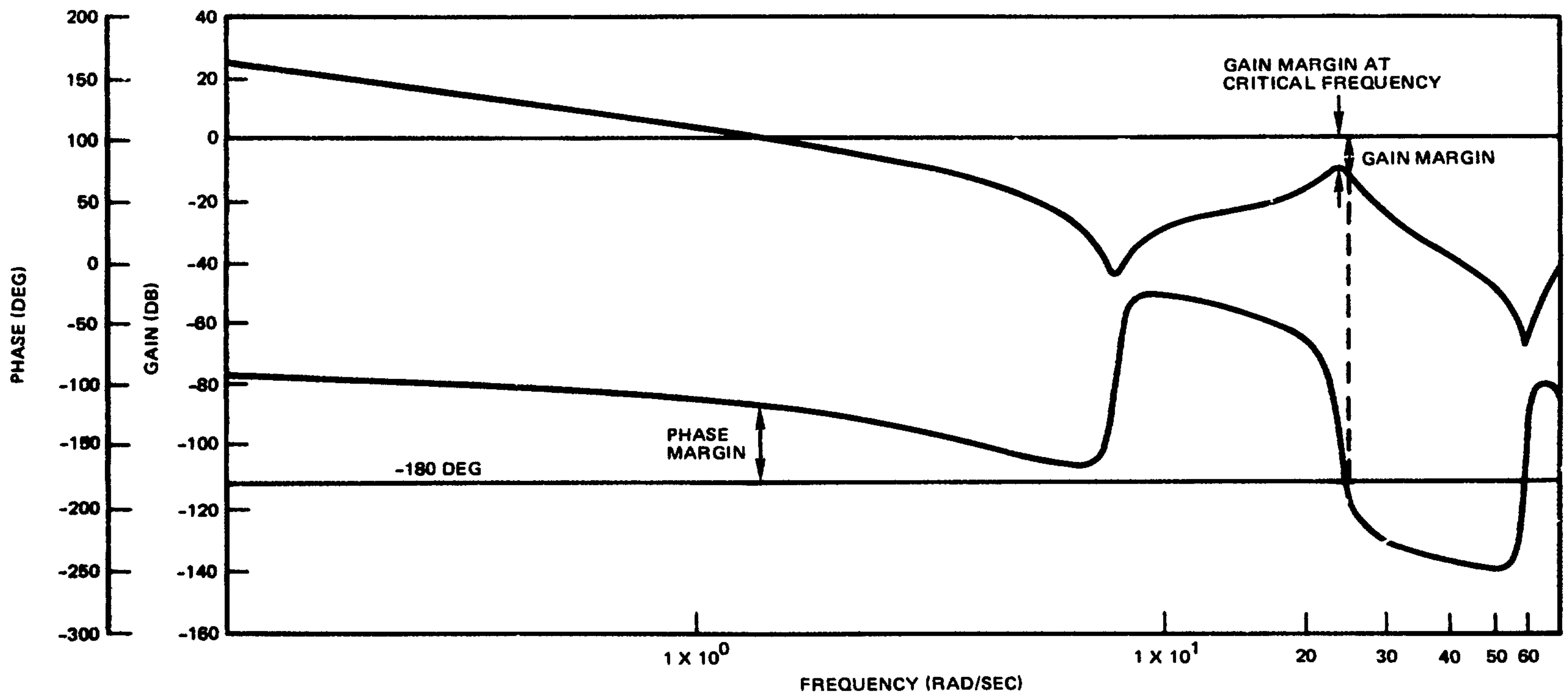

Figure 7. Typical Bode plot of engine/fuel system/drive train model.

The advantages of using supercritical shafts are several. They reduce the torque requirements (and hence the weight) of the tail rotor shaft for a given tail rotor power transr itted. Another important consideration is that the eccentricity of the shaft decreases drastically with respect to the center of rotation once the critical speed is crossed. At supercritical speeds, rotating shafts tend to be self-centering, resulting in reduced vibration and wear and tear of the component parts. This can be seen very simply by studying the motion of an eccentric disk (Reference 6).

Self-Centering of Supercritical Shafts — Solving a second-order force balance equation provides the motion of the center of disk. It is an ellipse described by the equation

$$\frac{x^2}{X^2} + \frac{y^2}{Y^2} = 1 \qquad (1)$$

where.

$$X = \frac{\left(\omega^2/\omega_{nx}^2\right)e}{1 - \omega^2/\omega_{nx}^2}$$

$$Y = \frac{\left(\omega^2/\omega_{ny}^2\right)e}{1 - \omega^2/\omega_{ny}^2}$$

$$\omega_{nx} = \sqrt{k_x/M}$$

$$\omega_{ny} = \sqrt{k_y/M}$$

6. Myklestadt, N. O., FUNDAMENTALS OF VIBRATION ANALYSIS, New York, McGraw-Hill Book Company, Inc., 1956.

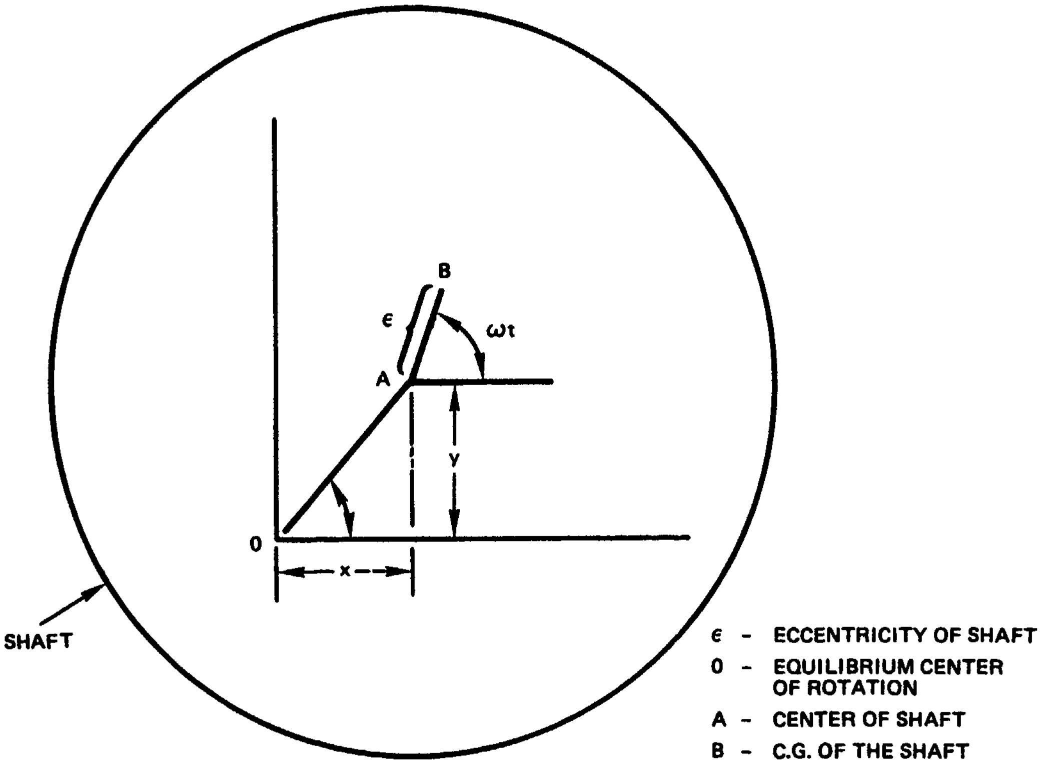

Figure 8. Schematic diagram of a rotating shaft.

Assuming X = Y (i.e., $\omega_{nx} = \omega_{ny}$) and for subcritical speeds ($\omega > \omega_{nx} = \omega_{ny}$), the center of disk and its center of gravity rotate about 0 in a circle (Figure 9).

For supercritical speeds ($\omega > \omega_{ny} = \omega_{ny}$) and for X = Y, it is seen that the points A and B again rotate as a rigid body but the point B is now closer to the axis of rotation than is point A. This is seen schematically in Figure 10.

When the speed of rotation increases without limit, the center of gravity of the disk (B) will approach the center of rotation (0).

In Phase 1 of the YAH-64 program, the tail rotor drive shaft (between the main transmission and the intermediate gearbox) was built with two unequal-length shafts coupled together. This was to allow for the folding of the tail boom. When this restriction was removed in Phase 2, four options were considered for the tail rotor drive shaft design (see Figure 11). Options 3 and 4 were eliminated because they could not support a decision to revert to the main engine cooling fan in lieu of the Black Hole IR suppressor system. Option 2(using two shafts of equal lengths coupled

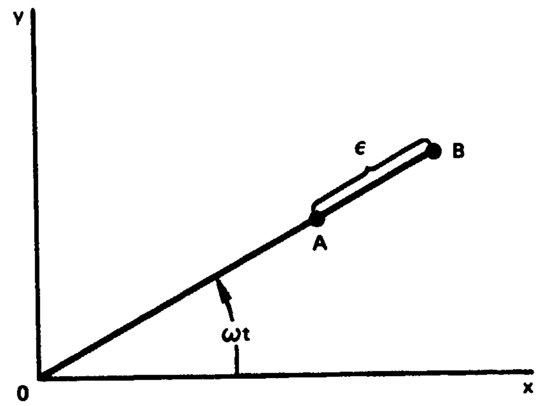

Figure 9. Relative positions of points 0, A, and B for subcritical speeds.

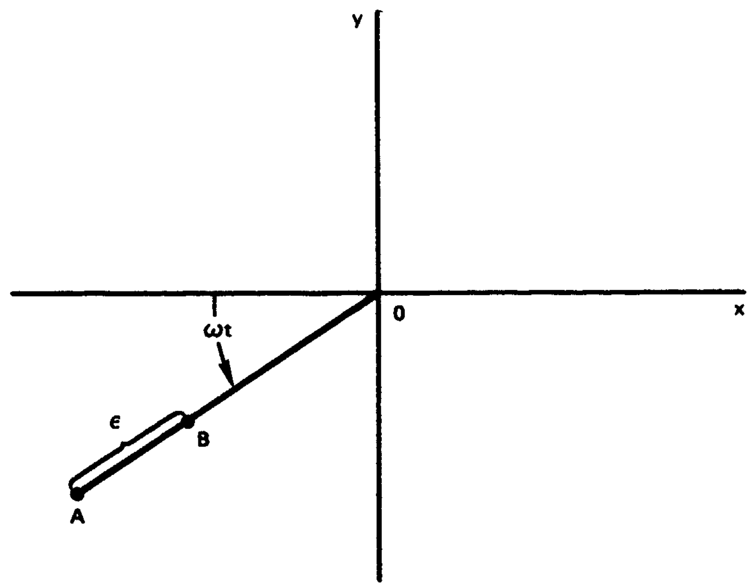

Figure 10. Relative positions of points 0, A, and B for supercritical speeds.

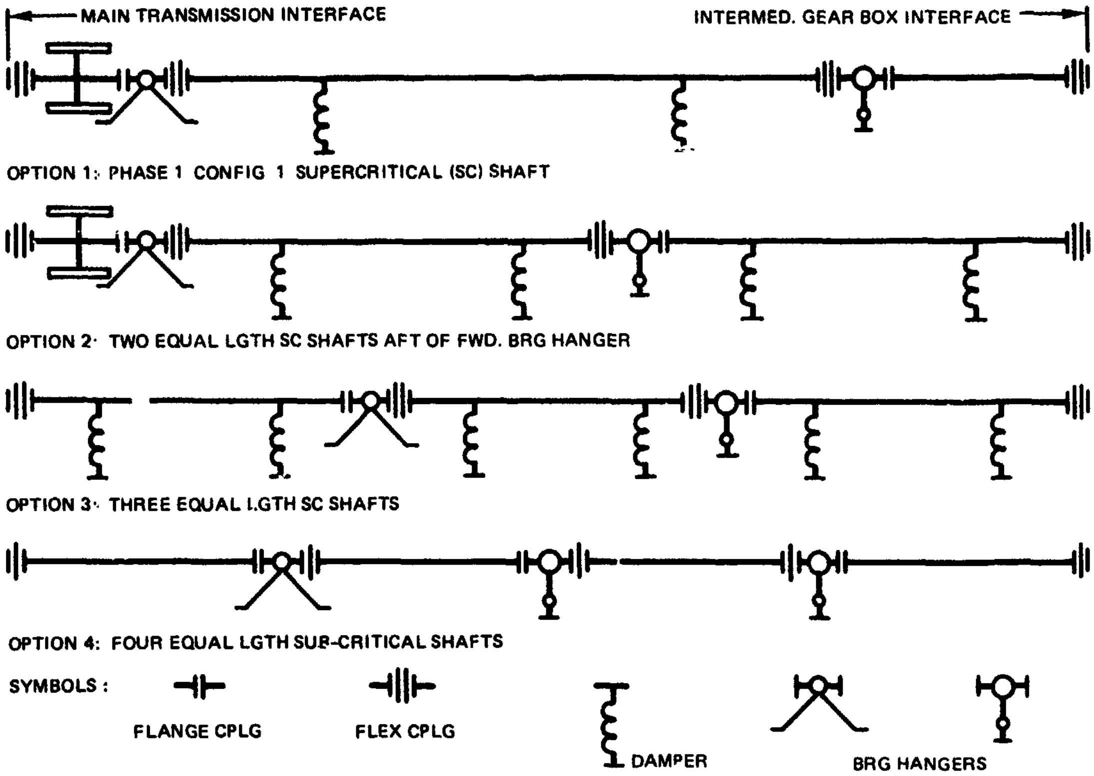

Figure 11. Four options for the tail rotor drive shaft design.

together) was chosen over option 1 (the existing Phase 1 design) due to economic considerations. This modification also changed the drive shaft modal frequencies such that in Phase 2 the tail rotor drive shaft operates between first and second critical frequencies as opposed to operation between second and third critical frequencies with the Phase 1 design.

Though supercritical shafts tend to be self-centering (Reference 6), care must be taken to maintain accurate modal balancing, especially at critical crossover frequencies. For this reason, a method has been devised at Hughes to obtain an accurate solution to the shaft balancing problem.

Balancing of the Tail Rotor Drive Shaft — Hughes Helicopters presently uses a hand technique for balancing its tail rotor shafts. This technique has successfully balanced the supercritical tail rotor drive shafts of the TH-55 and the OH-6A helicopters.

Traditionally, modal balancing techniques based on successive antimode balancing provided limited accuracy. The residual imbalance, after several modal balancing attempts, was unacceptable for the YAH-64 due to the more restrictive vibration requirements of the YAH-64 specifications.

The three factors that are the cause of shaft imbalance are:

- Distorted cross section
- Unsymmetrical wall thickness
- Shaft bow

These properties are obtained by determining the mass-center at several cross sections along the length of the shaft. Self-adhesive aluminum tape was applied along the shaft to make the mass-center congruent with the center of rotation. This procedure was applied manually to the tail rotor drive shaft of the YAH-64. The results of the manual process showed a high degree of accuracy in balance and suggested the need for automation of the balancing procedure for a substantial savings of cost and time.

Mathematical Formulation for Shaft Balancing — Here an outline is provided for the determination of the center of gravity for each cross section of the shaft. An exaggerated view of the asymmetry in a shaft cross section is shown in Figure 12. Some of the stations in the figure are defined as follows:

X_o = Distance from the reference plane (A-B) to the center of rotation (designed by the test setup)

X_1 = Distance from the reference plane to the outer surface of the shaft

X_2-X_1 = Thickness of the wall at azimuth angle θ

θ = Azimuth angle with respect to a reference coordinate system

X_R, Y_R = Coordinates of the midpoint between X_1 and X_2 with respect to the reference system.

$\overline{X}_R$, $\overline{Y}_R$, $\overline{\theta}$ = Coordinates of the center of gravity of the rotor shaft section.

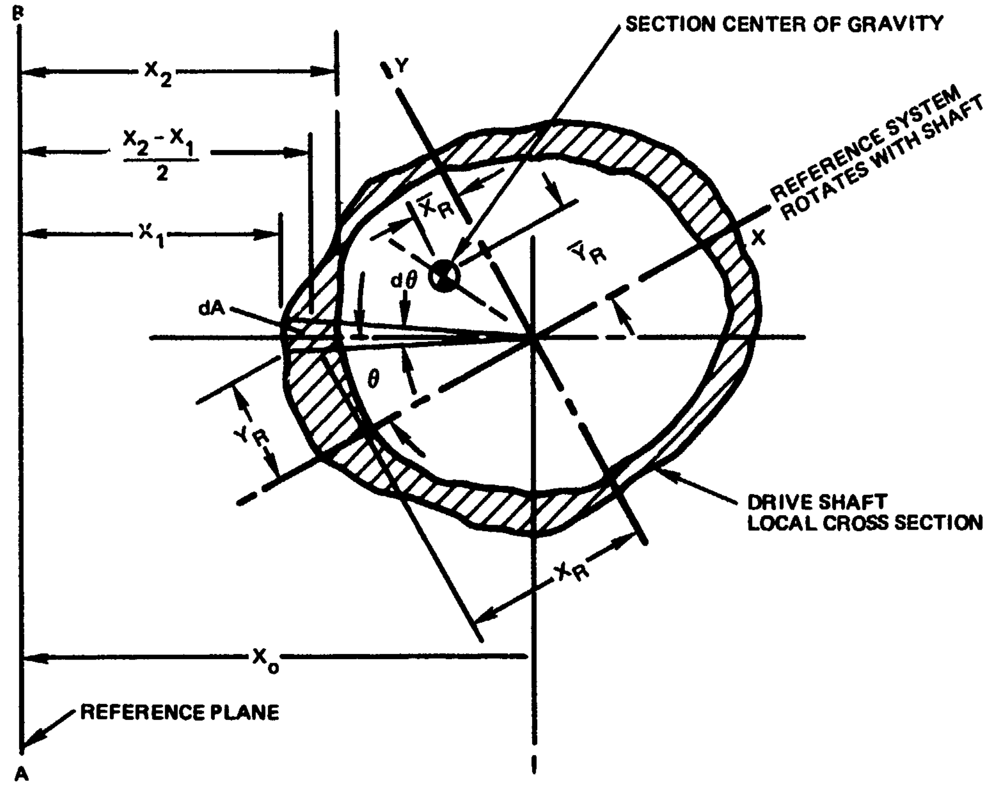

Figure 12. Shaft geometry for automatic balancing.

The coordinates of the center of gravity of the rotor shaft section are used to determine the azimuthal location and amount of the balancing weight. The coordinates are determined as follows:

$$\bar{X}_R = \frac{\text{Moment of the total section mass about the Y-Y}_{\text{axis}}}{\text{Total cross-sectional mass } (A_s)}$$

$$= \frac{\int_0^{2\pi} dA\, X_R}{\int_0^{2\pi} dA}$$

$$= \frac{\int_{o}^{2\pi} \left(X_2 - X_1\right)\left[X_o - \frac{\left(X_1 + X_2\right)}{2}\right]^2 \cos\theta \, d\theta}{\int_{o}^{2\pi} \left(X_2 - X_1\right)\left[X_o - \frac{\left(X_1 + X_2\right)}{2}\right] d\theta} \tag{2}$$

Similarly, $\overline{Y}_R$ is determined to be

$$\overline{Y}_R = \frac{\int_{o}^{2\pi} \left(X_2 - X_1\right)\left[X_o - \frac{\left(X_1 + X_2\right)}{2}\right]^2 \sin\theta \, d\theta}{\int_{o}^{2\pi} \left(X_2 - X_1\right)\left[X_o - \frac{\left(X_1 + X_2\right)}{2}\right] d\theta} \tag{3}$$

Define

$$\begin{aligned} \overline{R} &= \left(\overline{X}_R^{\,2} + \overline{Y}_R^{\,2}\right)^{1/2} \\ \overline{\theta} &= \tan^{-1}(\overline{Y}_R / \overline{X}_R) \end{aligned} \tag{4}$$

If σ_s is the density of the shaft material, W_B and θ_B are the balancing weight and its azimuthal location, respectively, and R is the radial location of the balancing weight,

$$W_B = \frac{A_s \sigma_s \overline{R}}{R}$$

and

$$\theta_B = (\overline{\theta} + \pi)$$

As explained before, this technique is considerably superior to the modal balancing method, especially at high speeds when accurate balancing is essential for low vibrational stress and reduced wear and tear of the component parts.

REDUCTION OF ROTOR-INDUCED VIBRATION LOADS

The vibration environment of the engine arises from two sources, that due to self-induced excitation such as engine unbalance, and that arising from the vibratory input from the airframe at the engine supports. The first problem is the responsibility of the engine manufacturer. But, it is the helicopter manufacturer's responsibility to minimize the second source, that of airframe response at engine supports. The primary source of airframe response is due to excitation from the main rotor. It follows that the vibration environment of an engine with respect to airframe response is directly proportional to the magnitude of rotor excitation.

For vibrations that occur at integral multiples of rotor speed, the principal source of resulting airframe/engine vibration levels is the rotor system. Here, harmonics of aerodynamic loads on the blade give rise to vibratory response of the blade. Since the blade is restrained at the root, blade responses result in root shears and moments, which feed from the rotor hub to the airframe as vibratory shears and moments. The resulting rotor-induced engine vibration velocities are seen in Figure 15. Hughes Helicopters has developed active and passive vibration isolators to limit this interface problem.

As the forces go from the rotating to the fixed fuselage system, the rotor system in steady state flight acts as a filter. For an N-bladed rotor system, the troublesome frequencies that filter through are those at N and 2N/rev, respectively. Harmonic analysis of the fuselage vibration loads has shown (Reference 5) that N/rev vibration of the airframe is the most critical. It can be shown that N/rev fuselage vibrations in the fixed system are a result of the N-1, N, and N+1/rev vibratory response of the blades in the rotating system. Several active and passive devices for reducing rotor-induced fuselage vibration have been suggested over the years by the various helicopter industries.

<u>Passive Vibration Isolator — The Pendulum Absorber</u> — Hughes Helicopters has developed the pendulum dynamic absorber, mounted on the root of the rotor blades and operating in the vertical plane, to minimize the helicopter vibratory loads (Reference 4). Other techniques like the control of the first and second mode natural frequencies by means of antimode

weights and by use of preloaded internal cables were considered. These approaches were evaluated in flight tests and found to be less effective than the vertical-plane pendulum absorbers. The following is a qualitative description of this system.

It is known that for a four-bladed OH-6A helicopter main rotor, the vertical and horizontal shears at the blade root at frequencies of 3/rev, 4/rev, and 5/rev induced 4/rev vibration in the fuselage. Contributing to the fuselage vibratory response are two primary factors, the magnitude of 3, 4, and 5/rev aerodynamic excitation of the blades, and the resulting root shears. For such an articulated rotor, flapwise 3/rev and 5/rev blade root shears induce 4/rev fuselage vibrations producing 4/rev pitching and rolling moments in stationary coordinates at the hub. The 4/rev blade root shears sum for the four blades to produce a 4/rev hub vertical force. With respect to in-plane blade root shears, the 3/rev and the 5/rev components of root shear combine to produce both a fore-and-aft and lateral 4/rev horizontal force in fuselage coordinates. In-plane 4/rev root shears sum over the four blades to produce a 4/rev yawing moment about the hub axis. The above information is summarized in Table 1.

From a study of the vibrational loads measurements in the cockpit, it is seen that the 4/rev rolling moment is the major source of fuselage vibration. Hence, the 3/rev and the 5/rev vertical shear forces can be considered as the primary source of vibration. The blade vertical bending at a frequency of 4/rev and blade chordwise bending at frequencies of 3/rev and 5/rev can then be ignored. It was also found that the first and second mode flapping natural frequencies are very near 3/rev and 5/rev. Based on the above information and an evaluation of several concepts, it was decided to use dynamic absorbers to reduce the first and second flapwise bending motions.

TABLE 1. SOURCES OF 4/REV FUSELAGE VIBRATION FOR A FOUR-BLADED ROTOR

Shear		Resulting 4/rev Load
Vertical	3/rev	Hub moment
	4/rev	Hub vertical force
	5/rev	Hub moment
In-Plane	3/rev	Hub horizontal force
	5/rev	Hub horizontal force

The dynamic vibration absorber works on the concept of adding a small mass (the vibration absorber) to a large mass where the uncoupled natural frequency of the small mass is chosen to be equal to the frequency of the disturbing force. Hence, two tuned pendulum absorbers were mounted on each rotor blade, one tuned to a natural frequency of 3/rev and the other tuned to a natural frequency of 5/rev. The net result is that the centrifugal loads of the pendulum absorbers diminish the blade transverse shear due to blade modal response.

Analytic solution using the vibration absorber was determined using the finite-element DART program. This was done in two stages. In the first stage the rotor was modeled (with aerodynamics included) to determine the blade root shears with and without the pendulum absorbers. In the second state the fuselage was mathematically modeled to determine the mobility between the rotor hub and the crew compartment. These mobility values, together with the hub shear forces, were used to determine the vibration levels in the crew compartment. It was found that at a forward speed of 100 knots, the inclusion of pendulum absorbers reduced the crew compartment vibration level by 72 percent. Flight tests show a vibration level reduction of about 50 percent with the pendulum absorbers, over a wide range of forward speeds.

The use of pendulum absorbers show a definite improvement in the vibration transmission from the rotor to the fuselage and, hence, the whole vibration environment of the helicopter. All the production Model OH-6A and its commercial counterpart, to and including the Model 500C helicopters, were equipped with pendulum dynamic absorbers.

Even before the installation of the pendulum absorbers on the five-bladed Model 500D helicopters, it was determined that the vibration levels were within acceptable limits. Hence, the pendulum absorbers were not installed. During prototype development of the YAH-64, pendulum absorbers were used on the rotor. Again, they were found to be unnecessary since the vibration levels were acceptable. The pendulum absorbers were taken off since their removal resulted in reduced weight and a saving in maintenance costs.

<u>Active Vibration Isolator - Higher Harmonic Pitch Control</u> — As seen in the previous section, the helicopter responds mainly to 4/rev vertical oscillatory loads (for a four-bladed rotor). Hughes Helicopters, in cooperation with NASA-Langley, has been investigating an active higher harmonic control system for the reduction of this oscillatory load (Reference

7). The proposed 4/rev active control system will be developed to simultaneously reduce 4/rev pitching moments, and fore-aft and vertical forces that contribute to vertical fuselage response.

The primary element in this active control device is a special purpose digital minicomputer. The minicomputer would solve for the 4/rev collective and cyclic inputs necessary to null the 4/rev pitching moments and lateral and fore-aft forces, all of which contribute to 4/rev vertical fuselage response. The solution procedure would incorporate an analysis similar to one currently being developed by Hughes while under contract to NASA/Langley.

It is planned to install three 4/rev (32 Hz) electrohydraulic actuators in series with the cyclic and collective control links below the swashplate control mixer if there exists sufficient impedance to prevent transmitting 4/rev actuator loads to the pilot. If sufficient impedance does not exist upstream of the actuators, it may become necessary either to locate the servos higher in the control system or to increase the existing upstream control system impedance with springs, masses, blockers, etc. The advantage of mounting the actuators below the mixer lies in the fact that all 4/rev collective and cyclic motions will be mixed as usual. Installing the linear actuators in the mixer system requires mixing commands from the minicomputer system. The software developed during the program will define the control sequence as well as establish control authority. The control sequence would include data sampling, analog-to-digital conversion, processing the solution, checking safety-of-flight limits, and digital-to-analog conversion of the solution signal. Control authority consists of establishing the vibration threshold below which the system will remain idle. Error and failure mode contingency plans are also elements of control authority. Figures 13 and 14 are diagrams of the active control system installation and its profile inboard of the OH-6A.

MOBILITY METHODS TO PRECLUDE ENGINE/AIRFRAME VIBRATION PROBLEMS

Mobility or impedance techniques provide an excellent tool either during preliminary design or development of an aircraft, should an engine/airframe interface problem arise. Such methods are increasingly being adopted by

7. APPLICATION OF HIGHER HARMONIC BLADE FEATHERING FOR HELICOPTER VIBRATION REDUCTION, Contract NAS1-14552, Report No. 8, Hughes Helicopters, Culver City, California, Report No. 8, March 1977.

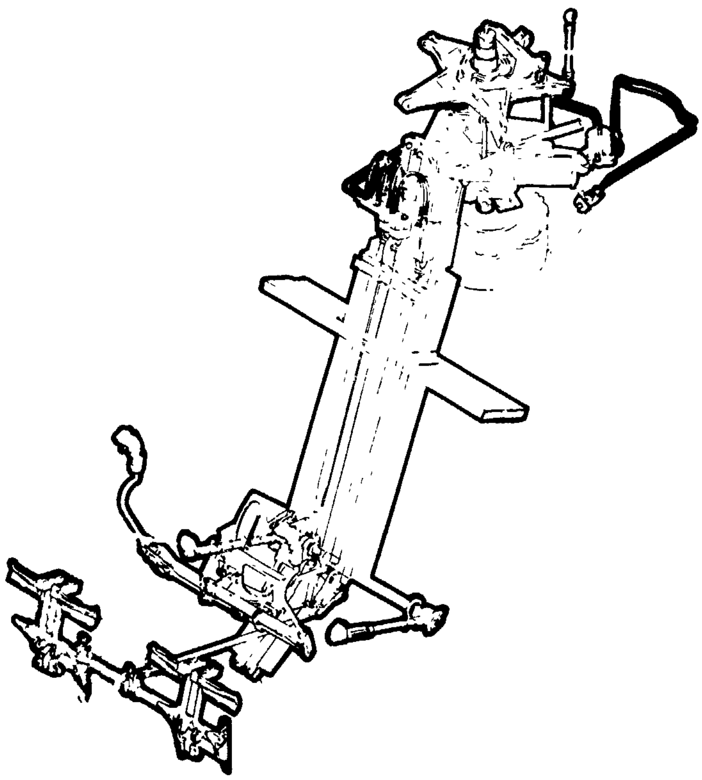

Figure 13. Higher harmonic active control system installation.

the helicopter industry to solve engine/airframe interface problems. Described in the following paragraphs is the approach taken by Hughes Helicopters with respect to application of mobility methods.

In order to appreciate the vibration environment of the helicopter and to prevent engine/airframe vibratory interface problems, an analysis technique was developed at Hughes Helicopters (Reference 4). Mobility methods were devised to study the OH-6A helicopter. This technique was used, not only to determine the vibrational loads at different helicopter locations, but also to improve the NASTRAN and DART mathematical modeling tools. The results provided in Reference 5 will be summarized here to provide OH-6A vibrational levels and also to present an outline of the procedure for future vibrational analysis for preliminary design. The results have been substantiated with flight test data.

Flight Test Data Evaluation — A T-63 engine was installed in the OH-6A prototype helicopter. Flight test data was gathered for a wide variety of flight conditions. The vibration loads at eight locations of the engine are

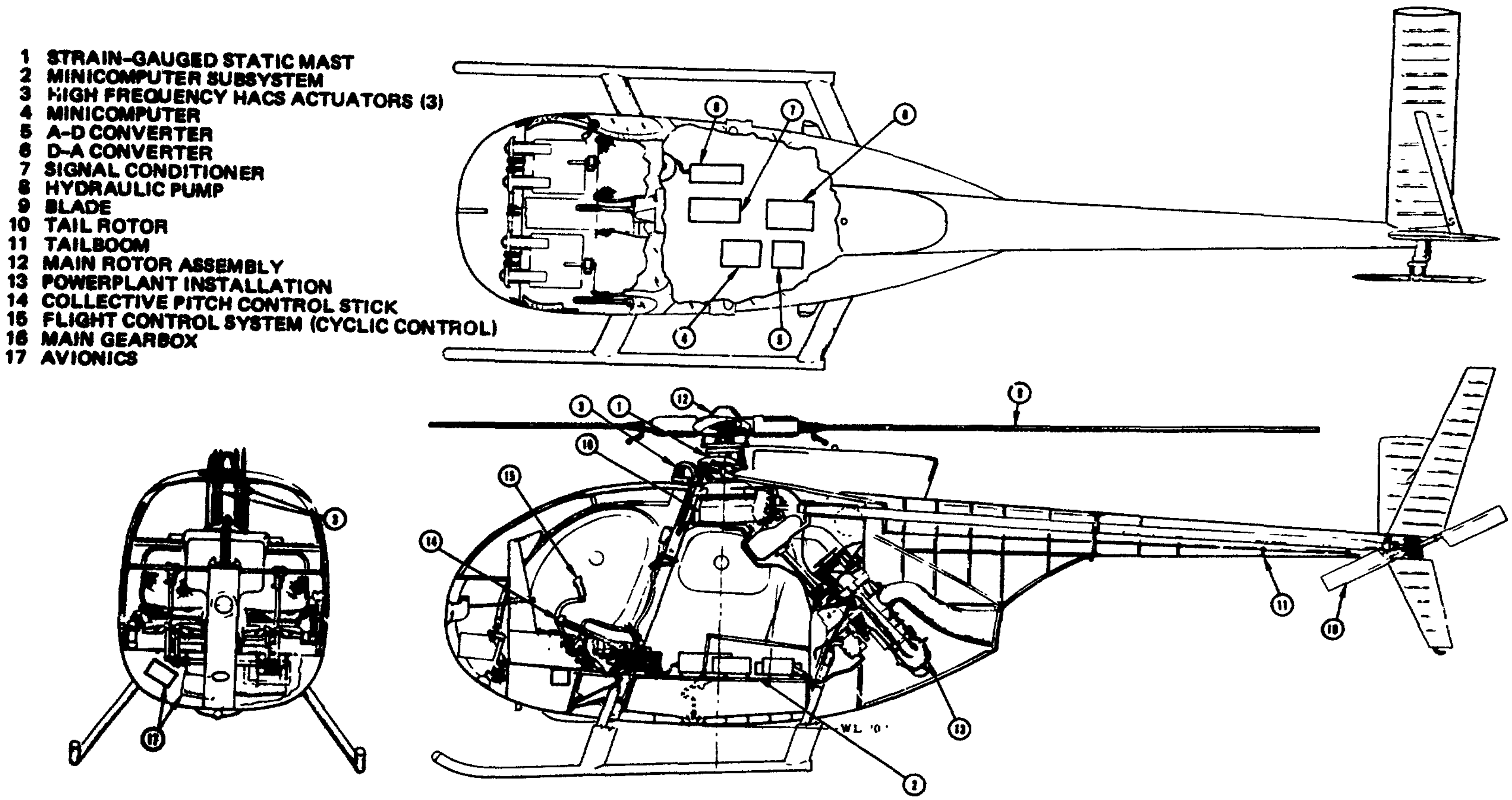

Figure 14. OH-6A with higher harmonic active control system inboard profile.

shown in Table 2. Discrete frequency vibration values for the cruise flight condition of 126 knots is shown in Figure 15.

The analysis of flight test data in Figure 15 will give a very good understanding of a typical vibration environment of the engine. Some of the important aspects of the analysis are:

- Relative contribution of airframe and engine-to-engine vibration.
- Amplitude versus discrete frequency at level flight from 8 to 800 Hz.
- Predominant engine mode shapes.

Table 3 lists the values of the measured discrete frequencies together with the corresponding sources of excitation. Since the lowest flexible bending mode of the T-63 engine is 127 Hz, it is reasonable to assume that frequencies of 8, 32, 50, and 100 Hz are associated with rigid-body modes that are excited by the main and tail rotor (i. e., airframe related) and the 800 Hz is associated with a flexural mode excited by the gas generator.

When the amplitude of the vibration at different engine locations for each vibration frequency is plotted, the modes corresponding to each frequency of vibration are obtained. It is found that the predominant responding modes are rigid-body modes, mainly in the vertical direction. Translation, pitch, and combination of translation and pitch are seen for the lower three modes. The data on the highest mode (800 Hz) is insufficient for accurate flexible mode shape prediction. Results are summarized in Table 4.

Figure 15 also provides the velocity of vibration at different engine locations at various frequencies. At 32 and 100 Hz, the compressor front vertical motions are significant. Vertical motion generally exceeds lateral motion for 8 and 32 Hz and reverse at 800 Hz.

The flight test data in Figure 15 shows that significant engine motion exists at 32 Hz, carried by the main rotor 4/rev excitation; the predominant responding mode is a rigid-body pitch mode. Appreciable engine motion exists at 100 Hz, caused by tail rotor 2/rev excitation; the predominant responding mode is a rigid-body pitch/translation mode.

Mobility Tests — These are laboratory (ground) tests conducted to acquire additional data to validate the NASTRAN structural dynamics model.

TABLE 2. ENGINE OVERALL VIBRATION VELOCITY (INCHES PER SECOND AVERAGE) FOR VARIOUS CONDITIONS

Conditions					Vibration Pickup Number and Location							
					1	2	3	4	5	6	7	8
Horse-power	IAS (mph)	Alt (ft)	Bal Cond	Maneuver	Comp Front Vert (Top)	Comp Front Lat (Right)	Acc G/B Vert (Btm Left)	Acc G/B Vert (Btm (Right)	Acc G/B Lat (Btm Left)	Acc G/B F&A (Top)	Turb Mid S/L Vert (Top)	Turb Mid S/L Lat (Left)
100	-	Grd	B	Tie-down ground run	0.60	0.50	0.35	0.55	0.45	0.32	0.45	0 45
100	-	Grd	U	Tie-down ground run	0.80	0.50	0.35	0.50	0.38	0.30	0.55	0.40
134	-	Grd	B	Tie-down ground run	0.60	0.50	0.30	0.60	0.35	0.35	0.50	0.40
134	-	Grd	U	Tie-down ground run	0.75	0.50	0.38	0.62	0.42	0.30	0.55	0.38
200	0	5000	B	Hover	0.85	0.83	0.40	0.56	0.47	0.50	0.60	0.55
134	44	5000	B	Hover	0.62	0.60	0.35	0.40	0.45	0.45	0.52	0.47
134	87	5000	B	Straight flight	0.60	0.55	0.33	0.45	0.55	0.50	0.60	0.60
227	120	5000	B	Straight flight	1.3	0.85	0.90	0.65	0.50	0.71	0.65	0.72
224	126	5000	B	Straight flight	1.7	0.82	0.60	0.80	0.52	0.70	0.85	0.65
-	-	100	B	Sideward flight - right	0.92	Δ	Δ	Δ	Δ	Δ	0.63	Δ
-	-	100	B	Sideward flight - left	0.93	Δ	Δ	Δ	Δ	Δ	0.65	Δ
-	0-10	100	B	Pedal turn - right	1.25	Δ	Δ	Δ	Δ	Δ	0.67	Δ
-	0-10	100	B	Pedal turn - left	1.0	Δ	Δ	Δ	Δ	Δ	0.71	Δ
-	-	Grd	B	Engine start to 100% N_2 rpm	0.68	0.60	0.38	0.95	0.40	0.65	0.50	0.42
-	-	Grd	U	Engine start to 100% N_2 rpm	0.80	0.60	0.45	0.70	0.47	0.62	0.45	0.45
-	-	Grd	B	Stabilized 100% N_2 rpm	0.70	0.45	0.40	0.47	0.45	0.58	0.39	0.30
-	-	Grd	U	Stabilized 100% N_2 rpm	0.80	0.40	0.45	0.30	0.40	0.62	0.35	0.40

B = Normal balance in rotors and drive shaft
U = Maximum allowable imbalance in rotors
Δ = Not recorded during this maneuver

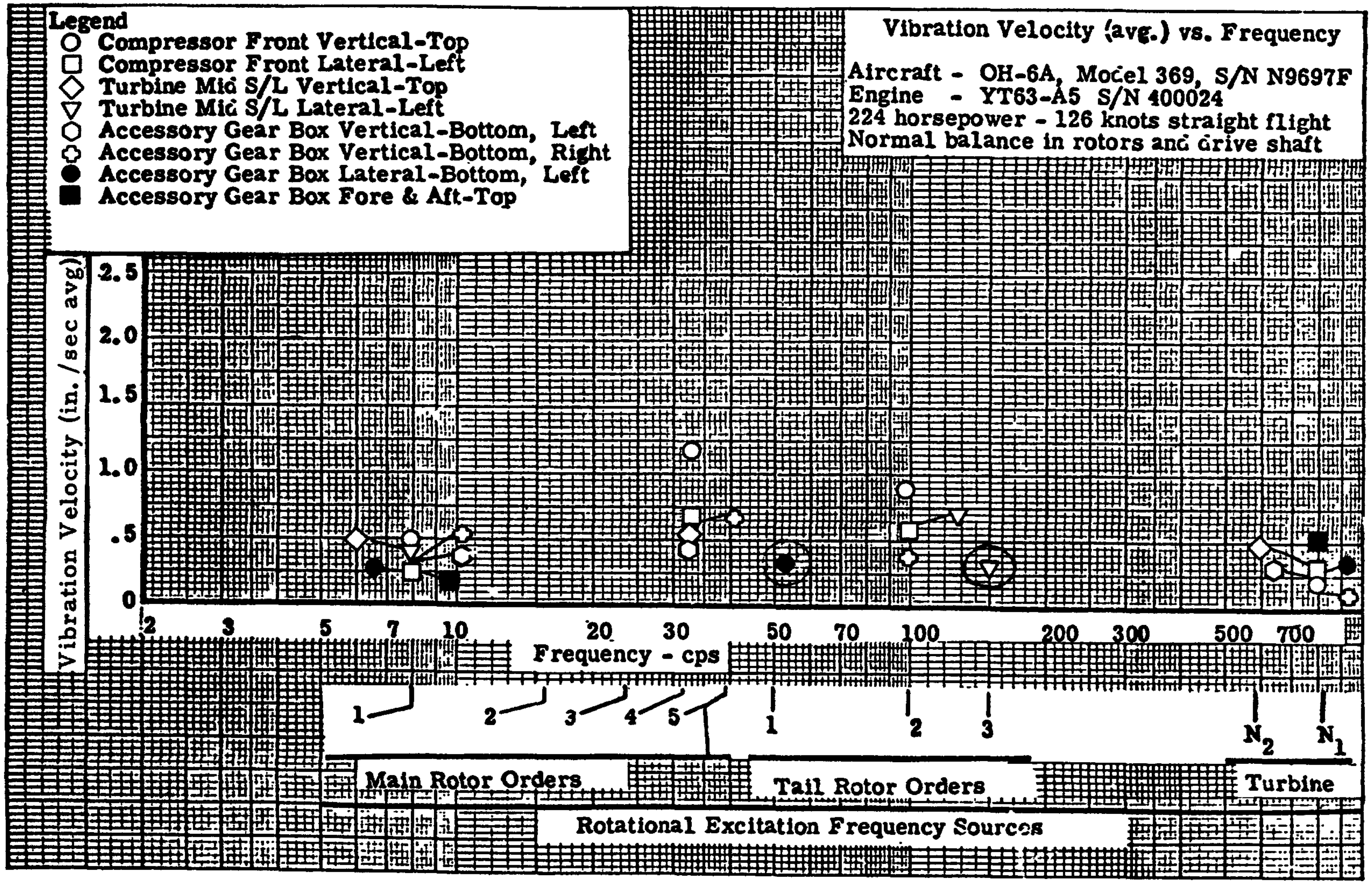

Figure 15. Vibration velocity (average) versus frequency.

TABLE 3. LISTING OF DISCRETE FREQUENCY DATA AND EXCITATION SOURCE

Frequency (Hz)	Excitation Source
8	Main rotor, 1/rev
32	Main rotor, 4/rev
50	Tail rotor, 1/rev
100	Tail rotor, 2/rev; engine shaft 1/rev
150	Tail rotor, 3/rev
800	Gas generator

TABLE 4. EXCITATION FREQUENCY, MODE SHAPE, AND EXCITATION SOURCE

Excitation Frequency (Hz)	Predominant Mode Shape (Vertical)	Relative Contribution - Airframe or Engine
8	Rigid translation	Airframe' main rotor, 1/rev
32	Rigid pitch	Airframe: main rotor, 4/rev
100	Rigid translation/ pitch	Airframe: tail rotor, 2/rev; engine drive shaft
800	Flexural	Engine: gas generator

Mobility is the velocity of a point on the structure in response to a force shaking the structure. If the motion is measured at the point where the force is applied, it is denoted as direct mobility. If the mobility is measured at a point remote from the point where the force is applied, the mobility is called cross mobility.

Direct mobility measurements are taken for the main rotor hub, the tail rotor hub, the three engine mount locations (left, center, and right engine mounts), engine/transmission coupling, and the engine power pad. Cross mobility is determined with oscillating force inputs at one other engine location and mobility measurements are determined at five other engine locations (Reference 5). The tests were conducted by mounting the helicopter in the static test rig. For all except the main rotor vertical excitation tests, the helicopter was suspended by a cable from a torsion-bar-type spring. An electrodynamic shaker (50 pounds force capability) was mounted on a hydraulic lift that positioned it for applying the oscillating forces to the main and tail rotors and to the engine shaft at the transmission. Accelerometers were used to make the mobility measurements. Mobility plots were drawn as velocity of response per unit force as a function of frequency. These results have been directly used for the following:

- To estimate, together with analytic models and flight test measurements of rotor mast forces, the vibration velocities at the different engine locations for which mobility data is available.

- To determine the accuracy of the NASTRAN model of the fuselage by comparing the experimental mobility values with those obtained by using the NASTRAN model for:

  1. Airframe without engine.

  2. Airframe with engine included.

Analysis of Mobility Test Results — Three typical mobility plots are shown in Figures 16, 17, and 18. The upper curves in these figures show the phase relationship of the velocity of the test point relative to the input force. The lower curves are plots of the mobility (i. e., the velocity in inches per second resulting from a 1-pound exciting force as a function of the frequency of the exciting force). It is seen that at the 1/rev main rotor exciting frequency (8 Hz), the vertical mobility is low (Figure 16); at the 4/rev frequency (32 Hz), the vertical mobility (Figure 16) is low, but the lateral mobility (Figure 17) is close to a peak.

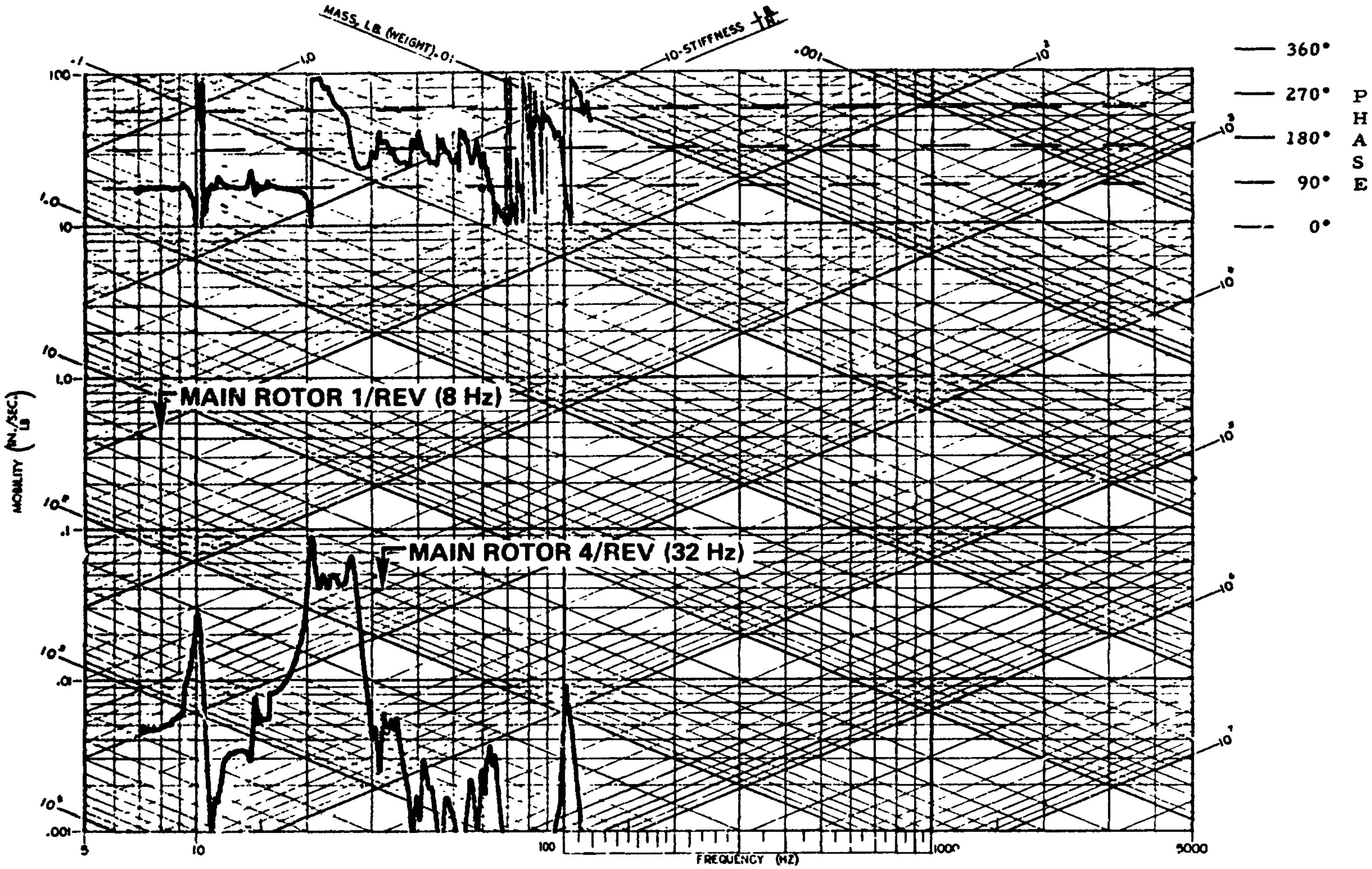

Figure 16. Engine front compressor — vertical mobility in response to main rotor longitudinal excitation.

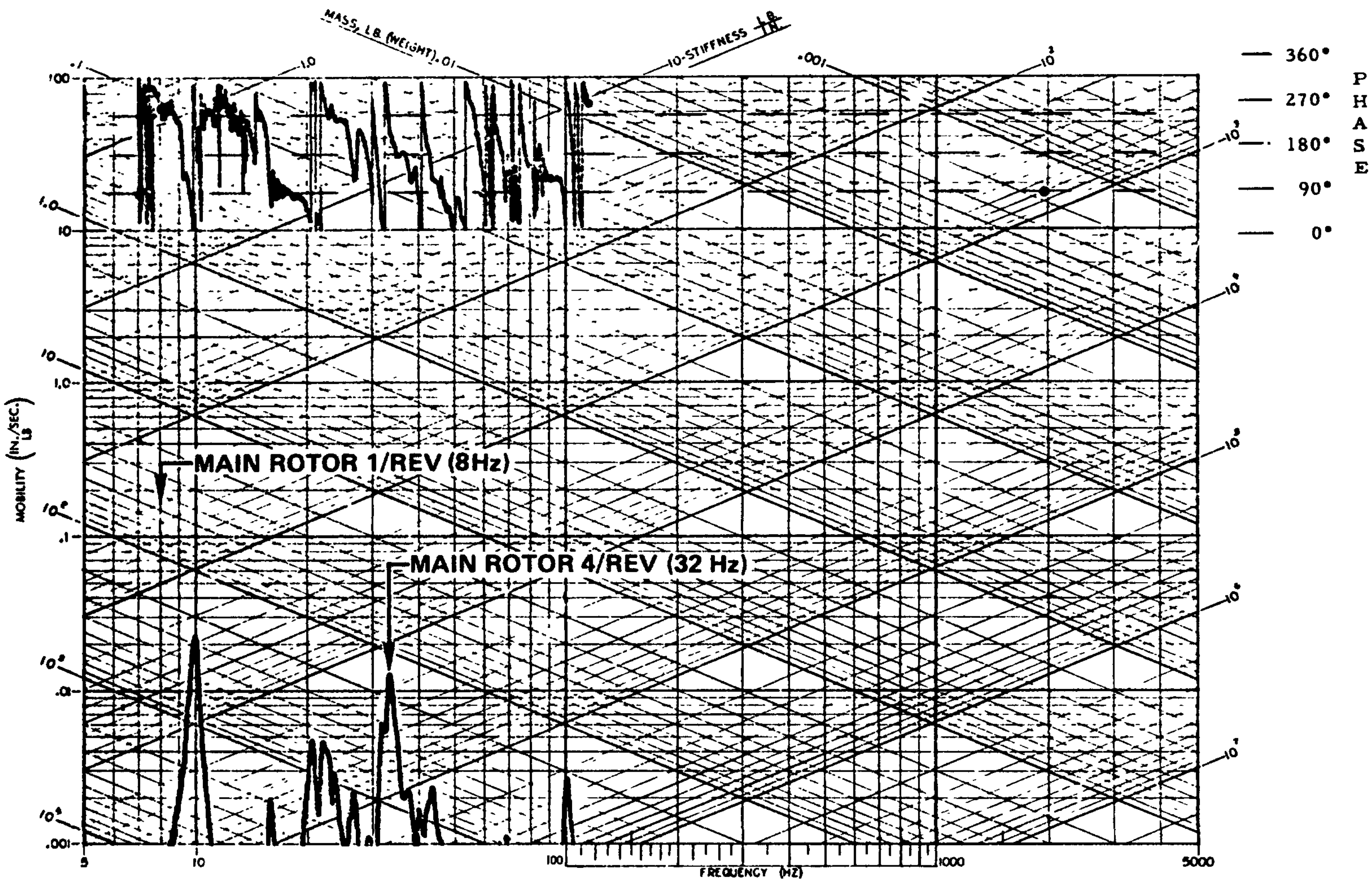

Figure 17. Engine front compressor — lateral mobility in response to main rotor longitudinal excitation.

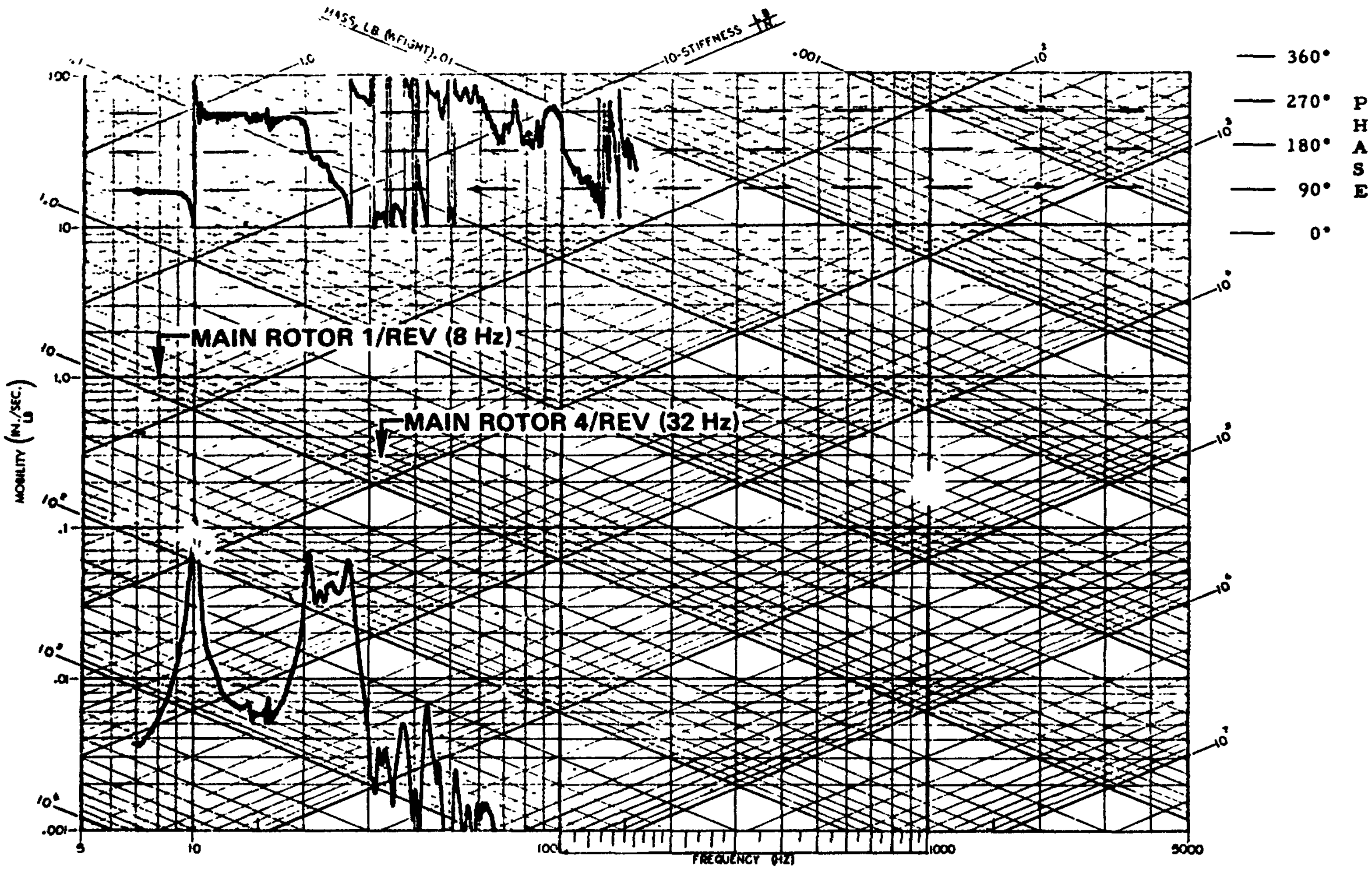

Figure 18. Turbine mid-split line — vertical mobility in response to main rotor longitudinal excitation.

The plots in Figures 16 and 17 disclose a very interesting situation. In each of these figures, the mobility is low at 4/rev (32 Hz), but much higher at a slightly lower frequency of 28 Hz. In other words, at a frequency of only 4 Hz below the major excitation frequency of main rotor 4/rev, an engine resonance is indicated with an amplification of at least 10. Phase plots determine this resonance as a rigid-body pitching motion. It is clear that if the engine mounting system pitch resonance frequency were only 15 percent higher, the engine vibratory motion would be significantly higher than allowable limits. Here the hard-mounted engine had its rigid-body modes below N/rev, where N is the number of main rotor blades. From the above and other studies, it was concluded that care must be taken to separate rigid-body engine modes from primary rotor excitation at 1/rev or N/rev.

Estimated Engine Vibration Spectrum — The applied periodic forces at the main rotor hub are derived from a combination of rotor hub forces determined analytically, and mast bending moments obtained from flight tests. The measured moments correspond to the rotation 3/rev and 5/rev rotor shear forces on the rotor hub. Since vertical 3/rev and 5/rev oscillatory forces were not measured because the pendulum dampers substantially reduced them, analytically derived vertical 4/rev, nonrotating, rotor forces are used. The mast bending moments in flight are found to be almost pure 4/rev signals. These hub forces are multiplied by the mobility values at 32 Hz, to determine the vibrational velocities at different engine locations (Reference 5). This technique has been used to determine the vibration loads for a typical mission operation of the OH-6A helicopter with a hard-mounted T-63 engine. Approximately 20 flight conditions in the load spectrum are shown in Table 5.

In order to be able to calculate the engine vibration velocities properly, the phase relationship between lateral, longitudinal, and vertical inputs should be included. However, accurate correlation with flight test vibration measurements was not achieved using this method. As an alternate, the limiting engine vibration value may be indicated by the sum of the longitudinal, lateral, and vertical responses (i.e., assuming all the responses to be in phase).

Analytical Dynamic (NASTRAN) Model — The purpose of developing a finite-element model of the airframe was to aid in the design of an airframe/engine interface. It is necessary to prescribe the dynamic criteria for installation before any airframe hardware is available for testing, to determine its dynamic characteristics. The only feasible method to determine these characteristics is by use of an analytical model.

TABLE 5. SPECTRUM OF COMPRESSOR VIBRATION* FOR TYPICAL MISSION OPERATION

Flight Condition	Percent Time	Calculated Compressor Motion** (in. /sec)
Hover		
Steady	2	0.21
Control reversal	1	0.28
Level flight		
30 knots	3	0.36
78 knots	21	0.41
100 knots	26	0.40
130 knots	17	0.83
Level flight,		
50 knots	2	0.93
130 knots	2	0.63
2g pull up, 100 knots	2	0.56
Level flight control reversal, 130 knots	3	1.70
Lateral flight	1	0.33
Maximum climb, 60 knots	6	0.43
Dive, 140 knots	1	0.97
Enter autorotation, 75 knots	1	0.31
Autorotation, 60 knots	3	0.59
Autorotation approach to landing	2	1.55
Autorotation turn		
40 knots	1	0.27
75 knots	1	0.60
120 knots	1	0.59
Miscellaneous	4	
Total	100	

*At 32 Hz (main rotor, 4/rev).

**Most adverse phase angle is assumed.

At Hughes Helicopters, DART and NASTRAN programs have been extensively used. Here, a brief overview of the results obtained with a NASTRAN model of the OH-6A helicopter is presented. As the causes of vibration problems tend not to be local with a component such as an engine, it was necessary to develop a complete airframe model. Presumably such models are developed today as part of the airframe design effort and do not need development for airframe/engine interface investigations only.

In the NASTRAN analysis, the airframe is modeled with finite elements following the contours of the actual structure (Reference 5). As the intent was to use the NASTRAN model methods for dynamic response, the first step was to develop a dynamic model with a reasonable correlation of natural frequency and mode shape with available test data.

Computed modal natural frequencies (for the airframe with and without the engine) versus test results are shown in Table 6. The first few mode shapes are shown in Figure 19 through 22.

Table 6 shows excellent agreement between the measured and the analytically predicted natural frequencies of modes 7, 8, and 10 (i.e., boom lateral bending, boom vertical bending, and boom torsion).

The effect on the natural frequencies of the superposition of the engine model on the airframe NASTRAN model is also compared. It is seen that the modal frequencies are only slightly influenced by the inclusion of the engine.

The accuracy of the airframe NASTRAN model is next verified by a study of the mobility plots of the analytic model with dynamic laboratory (ground) tests. A sample of the direct mobility plots are shown in Figures 23 through through 25. The detailed direct and cross mobility plots could be found in Reference 5. There is good qualitative agreement between the analytic model and dynamic test results for the direct mobility study. However, differences in the results indicate the need for higher degree of sophistication in the development of the NASTRAN model and an understanding of the limitations of the mobility testing techniques.

The engine is modeled as described in Reference 5. The modal coefficients are extracted from the engine mobility test data and geometric data. The engine model is assembled in a NASTRAN model and is used to produce mobility plots. Excellent correlation was achieved between 8 Hz (main rotor 1/rev) and 145 Hz (second engine bending mode) as seen in Figure 26.

TABLE 6. COMPARISON OF PREDICTED AND MEASURED NATURAL FREQUENCIES

	Natural Frequency (Hz)			
		Analysis		
Test Number	Test* Data	Engine Out	Engine In	Name
1-6	-	0	0	Rigid-body
7	8.9	7.92	7.66	Boom lateral bending
8	8.35	8.59	8.32	Boom vertical bending
9	ND**	11.76	11.69	LG antisymmetric
10	13.5	13.87	13.84	Boom torsion
11	ND	15.22	15.21	LG symmetric
12	ND	16.26	16.27	LG antisymmetric
13	23.0	18.51	16.77	Main rotor mast longitudinal
14	ND	18.79	18.83	Horizontal stabilizer chord bending
15	ND	20.35	19.81	Lower vertical stabilizer chord bending
16	-	22.29	21.45	Main rotor mast lateral bending
	17.4	-	21.80	Engine "rigid-body" vertical
	ND	-	23.23	Engine "rigid-body" lateral
17	ND	25.66	26.97	LG antisymmetric
18	ND	26.49	26.81	LG symmetric
19	ND	27.09	27.29	LG symmetric
20	ND	28.35	28.81	LG antisymmetric
21	ND	29.09	29.02	Upper vertical stabilizer chord bending
22	ND	33.60	32.66	Tail rotor drive shaft vertical bending
23	ND	34.76	34.73	Tail rotor drive shaft lateral bending
	35.1	-	-	Mast lateral
	38.5	-	38.82	Engine "rigid-body" longitudinal

*Source: References 3 and 5 **ND = Not determined in test.

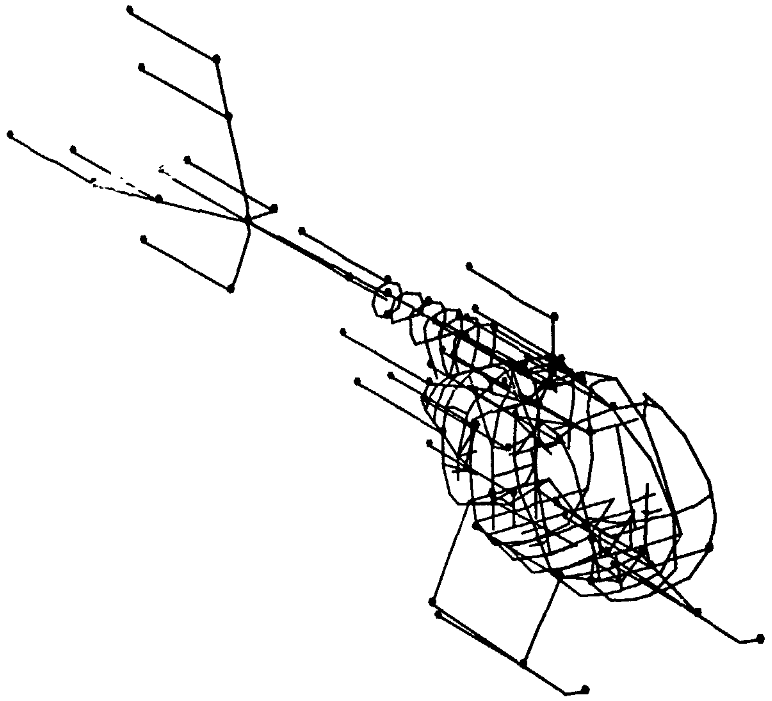

Figure 19. Rigid-body mode – longitudinal.

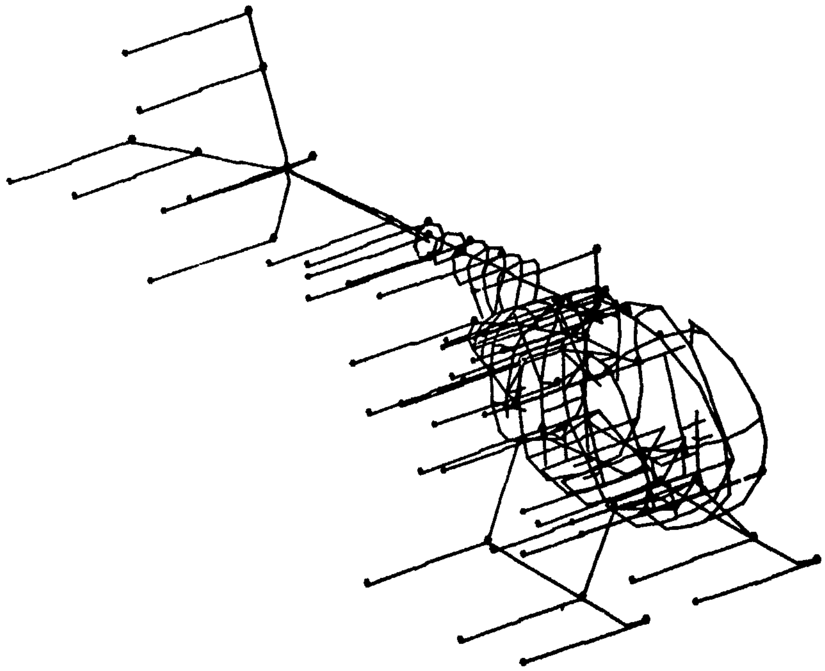

Figure 20. Rigid-body mode – lateral.

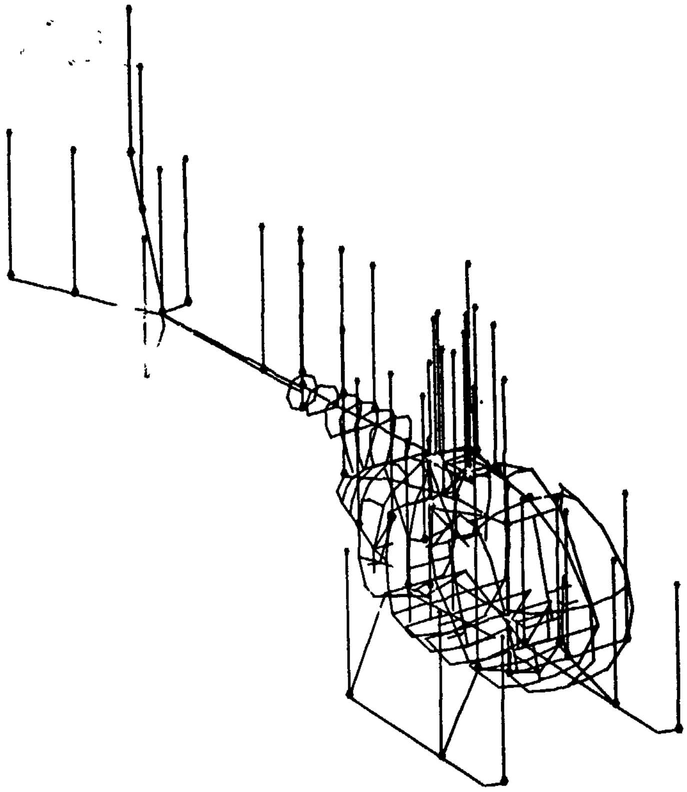

Figure 21. Rigid-body mode – vertical.

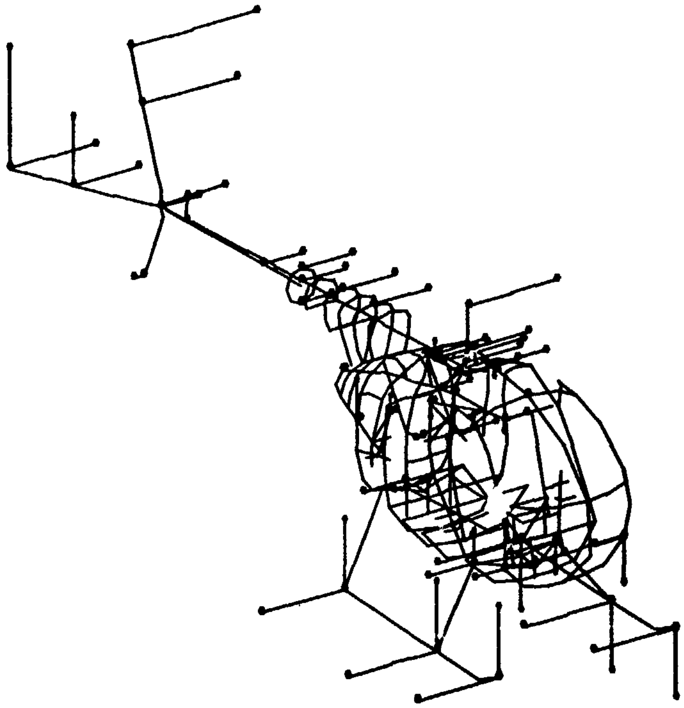

Figure 22. Rigid-body mode – roll.

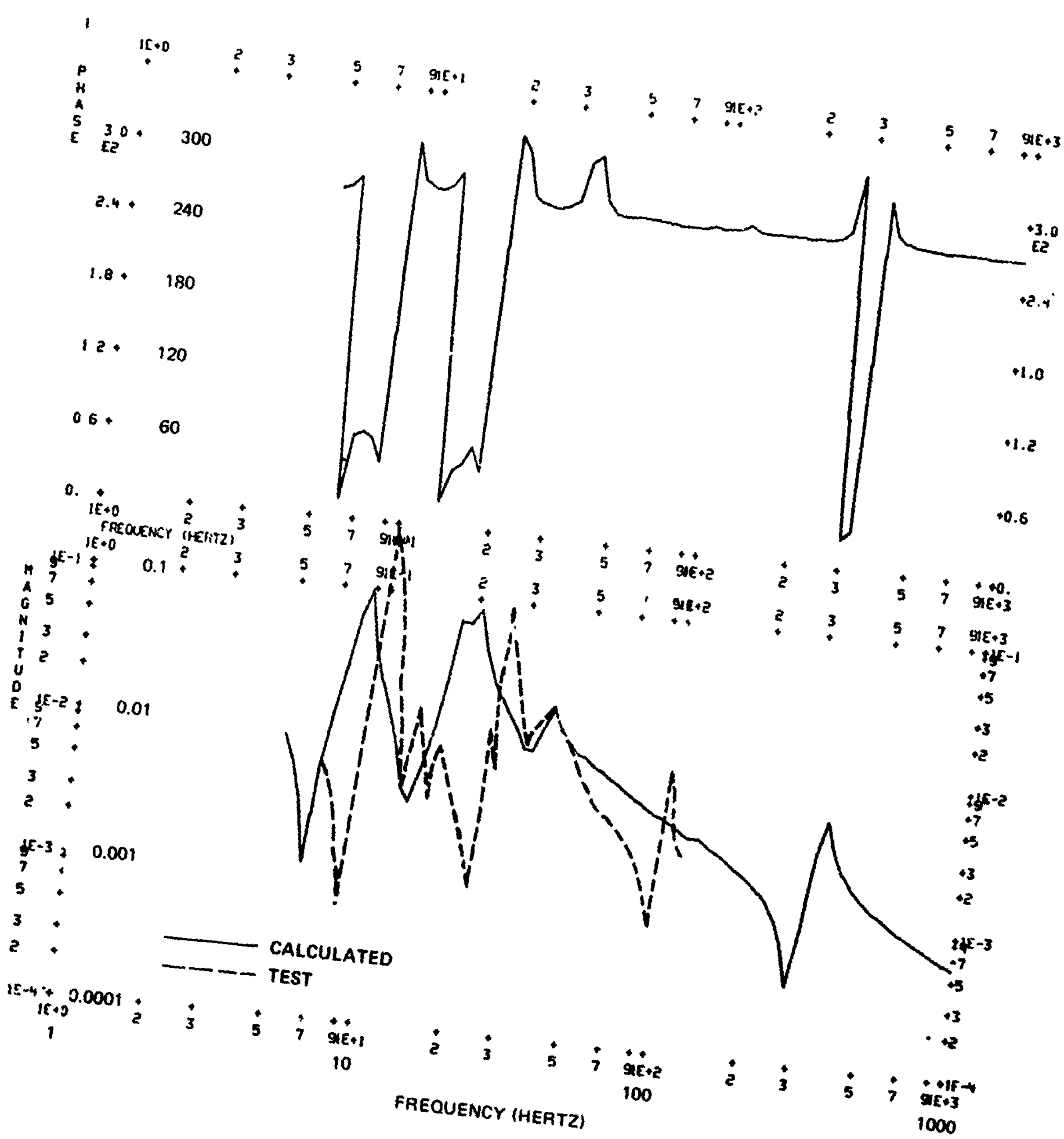

Figure 23. Direct mobility – main rotor longitudinal.

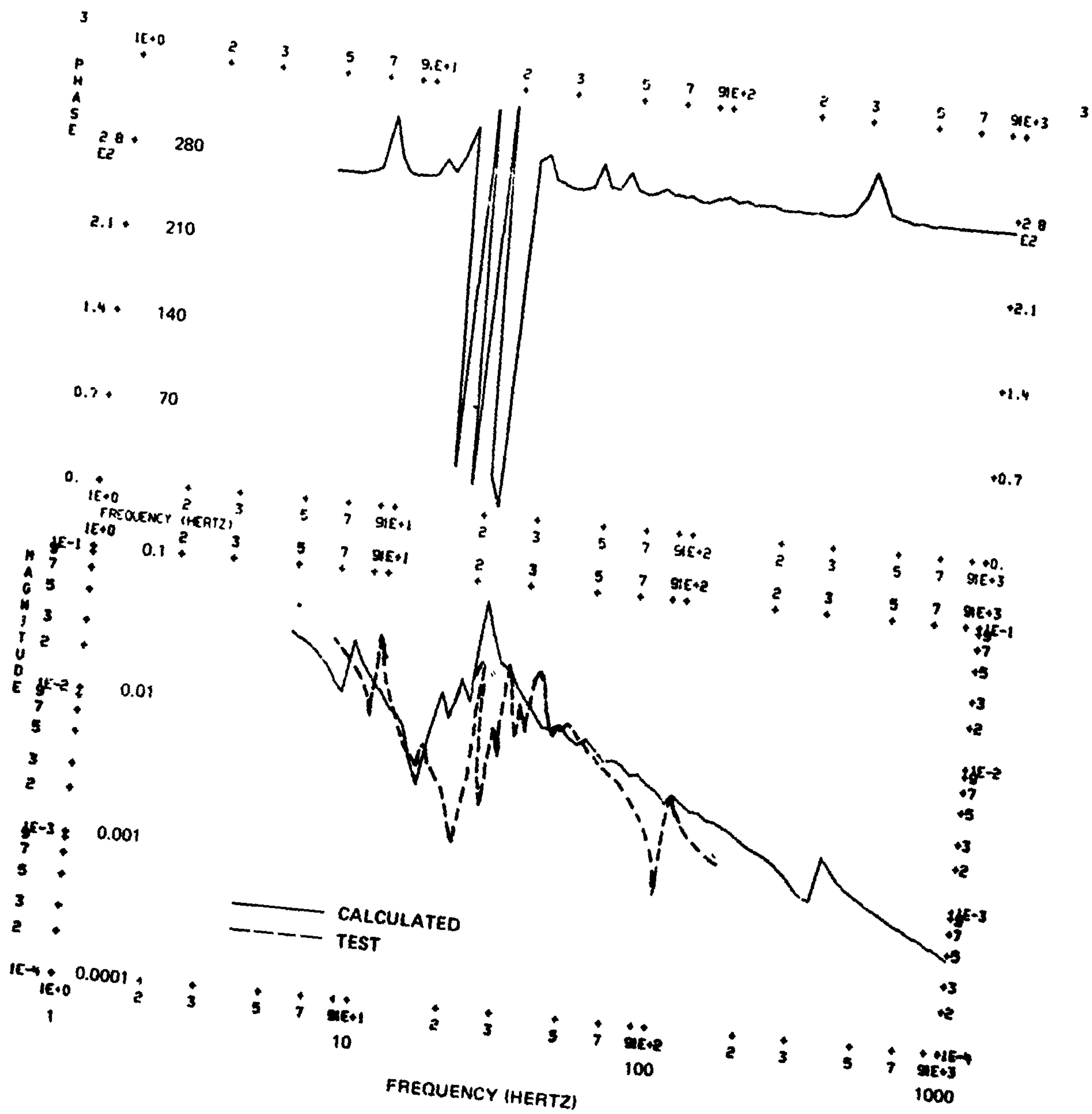

Figure 24. Direct mobility — main rotor lateral.

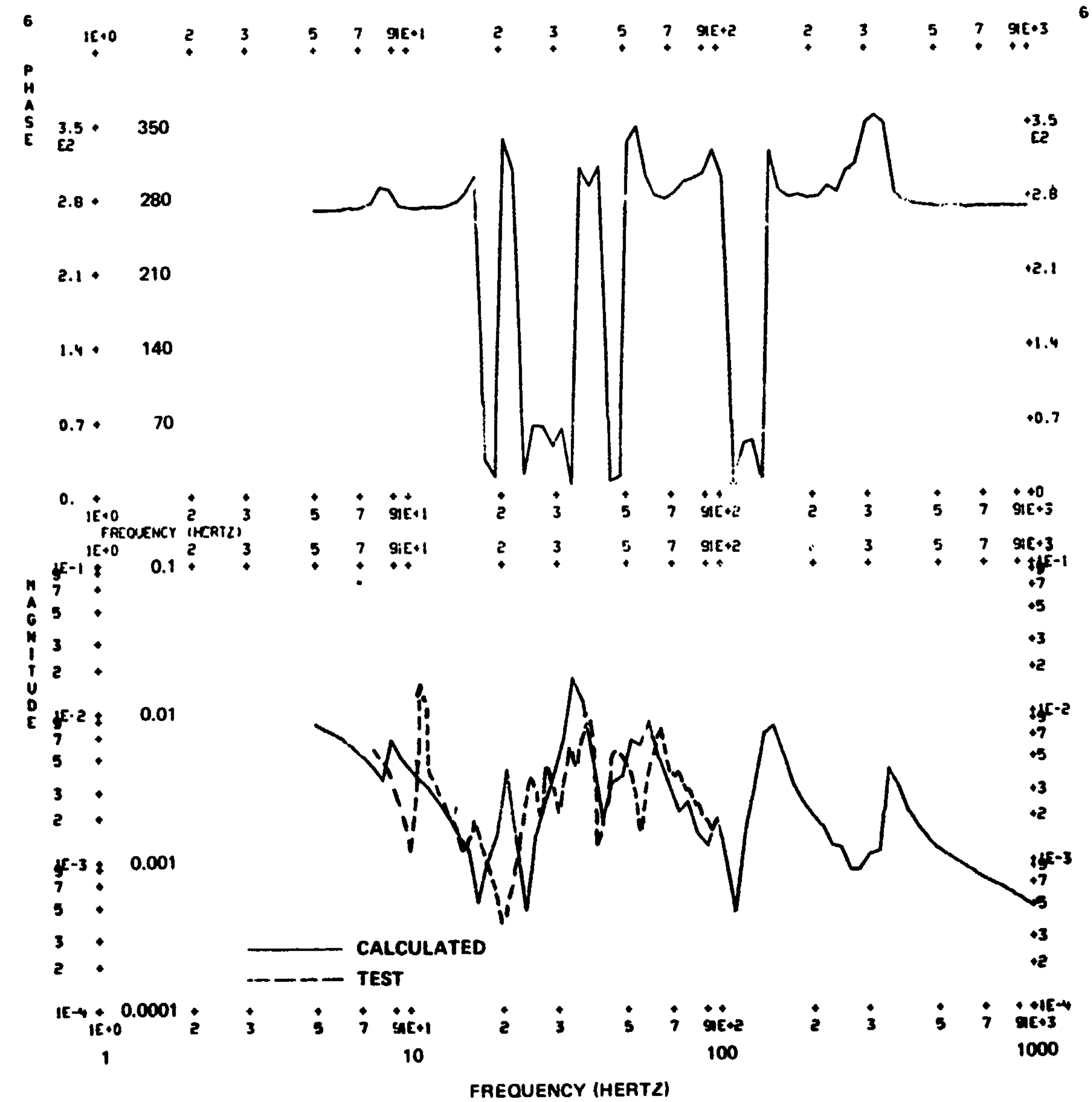

Figure 25. Direct mobility — main rotor vertical.

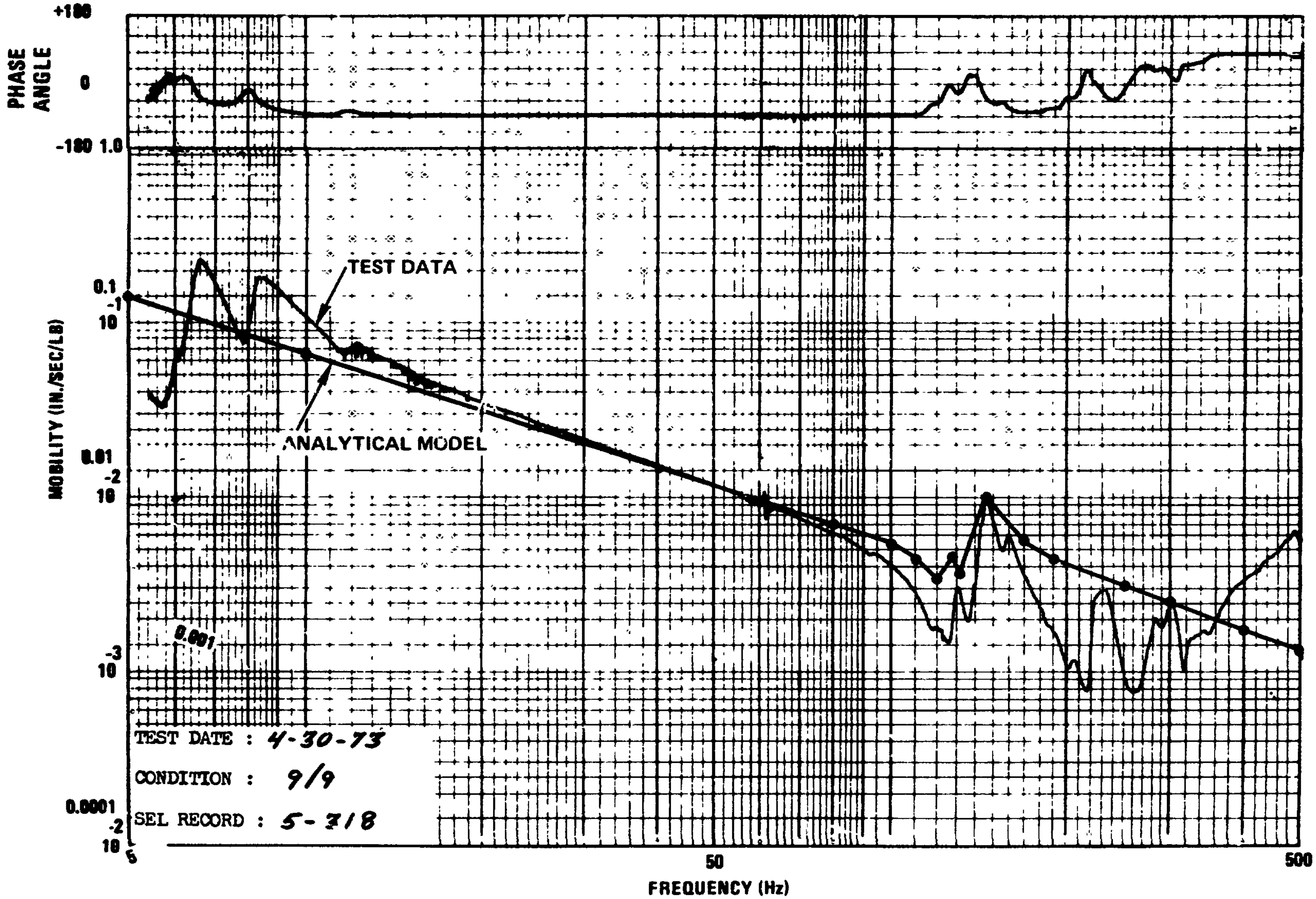

Figure 26. Correlation of engine model with test data.

The coupled engine/airframe NASTRAN model is next correlated with dynamic ground mobility test data (Reference 5) with good results.

With an accurate analytical model of the airframe/engine system, predictions can be made of the engine vibration forces based on analytically determined main and tail rotor hub forces. The airframe, engine, and engine mounting can be analytically modified (with corresponding hardware changes) to minimize, or ascertain within the vibration limits, the engine vibration loads for the different maneuvers encompassed in a typical flight spectrum.

The mobility results, together with the verification and use of analytical techniques using NASTRAN and DART computer programs, have been described in an effort to encourage the development of standardized methods of designing and evaluating the compatibility between the engine, drive train, and the airframe systems. A well-developed technique for preliminary design will undoubtedly be of value since it will save immensely in prototype design and later design modifications to overcome any engine/airframe/drive train interface problems. The technique outlined above provides one such method.

Although the NASTRAN and the DART programs were not fully utilized in the preliminary design of the YAH-64 because of time limitations, they are at present being used extensively in the analysis and prediction of the aircraft loads for various flight and conditions.

ENGINE SEAL PROBLEM

The design of the General Electric (GE) T700 engine allowed the possibility of designing an interface gearbox that could eliminate the seal on the nose gearbox. The T700 engines use a carbon-type seal with a pressurized cavity. However, if the seal should fail, both airflow and pressure at temperature would be impinged into the nose gearbox. During early use of the T700, the engine experienced a cracked seal failure at the output driveshaft. For the engine-gearbox installation, it took approximately 20 seconds to force all this oil from the gearbox through the vent. G.E. personnel determined that with a cracked engine seal, the maximum air flow was 3.0 cfm with a maximum pressure of 23 psi and with temperatures to 250 F. HH initially designed the engine nose gearbox with no seal at the interface. However, when learning of the engine seal failure, HH redesigned the nose gearbox for the YAH-64 helicopter. The redesign consisted of adding a seal to the input shaft to isolate the gearbox from the engine. Also, the breather was changed to give maximum effectivity when the maximum airflow from a failed engine seal was applied in the cavity at the interface of engine to gearbox. The final design successfully completed a pressure test with a 50-percent margin. Also, it should be noted that no T700 engine seals at the gearbox interface have failed during the flight testing of the YAH-64 helicopter.

CONCLUSIONS

With respect to the engine/airframe/drive train dynamics, the only significant problems encountered by Hughes Helicopters have been the fuel control stability and the shaft vibrational problems. These problems are being successfully resolved by proven engineering methods.

RECOMMENDATIONS

Hughes Helicopters (HH) has had limited problems that could be related to the dynamic interface of the engine/airframe/drive train systems and has no specific recommendations on the present engine specifications that relate to the dynamic interface of engine and helicopter. In this report are outlined several techniques that have been developed at HH to prevent engine/airframe/drive train compatibility problems. Some of these techniques are listed here as recommendations to provide engine/airframe/drive train compatibility:

- The use of rigid mounts and structural flexure coupling elements rather than spherical splines in the drive train to reduce the risk of instability at supercritical speeds and the need for stringent damping requirements.

- Application of supercritical drive shafts to alleviate imbalance and to reduce drive shaft weight.

- Mobility or impedance techniques for direct measurement of the compatibility between engine, drive train, and airframe systems.

- Reduction of rotor-induced vibration loads by the use of passive and/or active vibration isolation systems.

It is HH understanding that the work reported on was also carried out by all the other major helicopter manufacturers. HH recommends that upon completion of this program, the Government fund a joint contract to a helicopter manufacturer teamed with an engine manufacturer. The purpose of this contract would be to compile the findings of the work accomplished under the present contract and from this establish guidelines for future specifications for engine/airframe/drive train compatibility. HH suggests that this project be refereed by the Government and that during the conduct of the work periodic reviews be held at Applied Technology Laboratories. Further, HH recommends that non-participating helicopter and engine manufacturers be invited to participate in these reviews.

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LIST OF SYMBOLS

Q_1	Engine shaft torque.
J_{PT}	Engine shaft inertia.
N_P	Engine shaft rpm.
K_F, D_1, J_C	Spring, damping, and inertias respectively of the engine shaft and transmission coupling system.
K_T, D_2, J_T	Spring, damping, and inertias respectively of the transmission system.
K_{HT}, D_3, J_{HT}	Spring, damping, and inertias respectively of the tail rotor shaft system.
K_{HM}, D_4, J_{HM}	Spring, damping, and inertias respectively of the main rotor shaft system.
K_{CM}, D_{HM}	Spring and damping of the main rotor lag hinge.
K_{CT}, D_{HT}	Spring and damping of the tail rotor lag hinge.
D_{AT}, J_{TR}	Tail rotor aerodynamic damping and inertia.
D_{AM}, J_{MR}	Main rotor aerodynamic damping and inertia.
N_{TR}, N_{MR}	Tail and main rotor rpm respectively.
k_x, k_y	Spring stiffness of rotating shaft in the x and y directions respectively.
M	Mass of rotating disk.
ϵ	Eccentricity of the center of mass with respect to center of rotation of disk.

x, y	Coordinates of the center of a rotating, eccentric shaft.
X, Y	Major and minor axis lengths of the ellipse describ described by the center of a rotating, eccentric shaft.
ω_{nx}, ω_{ny}	The two natural angular frequencies in the x and y directions respectively.
X_o	Distance from the reference plane (A-B) to the center of rotation of shaft to be balanced.
X_1	Distance from the reference plane to the outer surface of the shaft.
$X_2 - X_1$	Thickness of the wall at azimuth angle θ.
X_R, Y_R	Coordinates of the midpoint between X_1 and X_2 to the reference system.
$\overline{X}_R, \overline{Y}_R, \overline{\theta}$	Coordinates of the center of gravity of the rotor shaft section.
R	Radial location of balancing weight.
W_B, θ_B	Balancing weight and azimuthal location respectively of the balancing weight.
θ	Azimuth angle with respect to a reference coordinate system.
θ_c	Collective pitch.
ω	Shaft rotational frequency.
$d\theta$	Small angle subtended at the center of reference system by elemented area dA.
σ_S	Density of the shaft material.

PROBLEM SUMMARY

Date	System/Aircraft Description	Problem
January to August 1975	Engine/main rotor drive system of the HH Model 500D Helicopter.	To maintain torsional oscillations at acceptable limits while maintaining adequate engine power response during transient power changes.
September 1975	Fan shaft on which the fan for the infrared suppressor was mounted on the Model YAH-64.	Resonance of the shaft forward end vertical natural frequency with the shaft rotational speed, causing fatigue failure of the shaft supports.
January 1976	Auxiliary Power Unit (APU) shaft connecting the APU drive unit to the drive system on the Model YAH-64.	Inaccurate determination of shaft bearing support stiffness, resulting in high vibration loads and failure of the diaphragm coupling of the shaft.